FLUORESCENT LIGHTING MANUAL

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Flourescent Lightining Manual

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BY

CHARLES L. AMICK

Nela Park Engineering Department
General Electric Company

First Edition
Third Impression

McGRAW-HILL BOOK COMPANY, Inc.
NEW YORK AND LONDON
1942

FLUORESCENT LIGHTING MANUAL

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THE MAPLE PRESS COMPANY, YORK PA.

To

JANET

and

JOAN MARGARET AMICK

PREFACE

In the four years since their introduction, fluorescent lamps have overwhelmingly captured the public's lighting fancy. This popular interest is a natural result of the illumination possibilities —both utilitarian and decorative—that these sources offer. But the characteristics of fluorescent lamps are so different and the new lighting concepts so varied that an understanding of the whole subject is essential if all the possible benefits are to be achieved.

This manual is written for everyone interested in fluorescent lighting—manufacturers, contractors, dealers, installers, and users—with the hope that greater understanding will help point the way to more effective installations and maximum customer satisfaction. To this end, fundamental "background" knowledge and practical installation design and servicing information are presented in simple language. The writer also attempted to interpret some of the basic philosophy of illuminating engineering with regard to footcandle standards and lighting quality for the benefit of those readers whose interest in lighting is of fairly recent origin.

It is the principal purpose of this manual to provide a ready reference source for the fundamental knowledge useful in solving the problems that arise in contemporary fluorescent lighting practice. Of course, certain of the data (such as lumen outputs, etc.) are subject to change—indeed even some principles of illumination practice now generally accepted may be altered by future knowledge and developments and improvements in lamps and the lighting art. However, the writer has not hesitated to stress certain lighting-quality essentials influencing the attainment of optimum illumination effectiveness and customer satisfaction where those essentials seemed basic and likely to remain "in good company" for some time.

The writer has been entirely dependent on the many engineers of the Nela Park Engineering Department, General Electric Company, as the source of the information given. Extensive

use has been made of material published by these associates, chiefly in *Illuminating Engineering* and the *Magazine of Light*, and the writer gratefully acknowledges the source of such information by specific references. It is realized that explicit credit mentions may inadvertently be incomplete.

The writer is particularly appreciative of the help given by A. B. Oday and C. E. Weitz in reading the manuscript and proof. Their constructive suggestions and interest have been most inspiring. Gratitude is also expressed to Misses Alice Harris, Elsie Linden, and Ida Maye Newkirk for diligent efforts in the mechanical preparation of the manuscript and to Miss Kaye Leighton and Floyd Phare for many of the illustrations included.

CHARLES L. AMICK.

NELA PARK, CLEVELAND, OHIO,
March, 1942.

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FLUORESCENT LIGHTING MANUAL

CHAPTER I

THE FLUORESCENT LAMP

Early Fluorescent Lamps.—It all started with a shoemaker in 1602. Casually he flashed his lantern on a rock which to his amazement glowed with an eerie light. After his fright had passed, he became curious and tried to discover the reason. Although he failed, the study was begun which 50 years later led to the discovery of fluorescence.[1] Thus, the phenomenon of fluorescence was recorded several hundred years ago. In fact, the principle was incorporated in a lamp as early as 1896. An edition of the Encyclopaedia Britannica printed in 1904 contains this item, abstracted in part:

> FLUORESCENT LAMP, an electric lamp invented by Thomas A. Edison in 1896. It has a bulb of glass, resembling that of the ordinary incandescent electric lamp except that it is more circular and that the wires enter at a greater distance apart. There is no platinum film to become incandescent, the light being obtained by coating the inside of the glass bulb with tungstate, against which the lines of force of the currents from the wires are directed, so that the molecules of air strike the tungstate, rebounding in all directions, and causing fluorescence. . . . The whole globe glows with a white light that bears a strong resemblance in appearance to sunlight. . . . No perceptible heat is developed by the light. . . . It is also claimed that the new lamps will last much longer than the incandescent since there is no filament to burn out.

This excerpt shows that Edison foresaw the development of the modern fluorescent lamp. Some of his intimations became important clues as scientists struggled to overcome the many

[1] A definition of "fluorescence" and other terms used in this manual will be found in the Appendix.

obstacles that faced the development of a commercially feasible fluorescent lamp. It was known that many hundreds of organic and inorganic substances, rocks, and chemicals would fluoresce, or become luminous, when exposed to certain radiations, and fluorescent materials had long been used in X-ray screens and cathode-ray tubes and for producing spectacular effects in advertising and display work. Many scientists had dreamed of a cool, efficient fluorescent light source, and finally, after many years of patient research during which chemists, physicists, and engineers brought together the related fragments of knowledge, the modern fluorescent lamp was introduced in April, 1938, and lampmaking machinery was developed to produce it in quantity.

In the 4 years since fluorescent lamps were announced, continued research and development have been responsible for steady improvements in the efficiency of light production, lamp life, and lamp quality. The originally announced line consisted of three wattage sizes; the present line has three times that number in a range of bulb sizes and wattages to fill a wide variety of fluorescent-lighting requirements. From a lamp and fixture market that did not exist 4 years ago, fluorescent lighting has grown to an estimated $250,000,000 business for 1941. Few, if any, industries have grown at a comparable rate.

Present Lamp Sizes.—Figure 1 shows the present standard line of fluorescent lamps, giving the wattage, diameter, and length of each size. Although fluorescent lamps of other sizes have been made for certain specialized applications, the present variety of sizes and wattages is felt to satisfy many of today's needs for a fluorescent light source, and proposals for new types must be closely examined in terms of limits in size, acceptable efficiency, etc.

The 14-watt 15-in. lamp was originally designed for 64-volt train-lighting circuits but now offers many interesting possibilities for application in floor and wall lamps, bracket lamps, etc., where two lamps can be used in series on 110–125 volt alternating current or direct current circuits. For this combination, a small filament lamp is employed as resistance ballast instead of the usual type of fluorescent auxiliary.

Fluorescent-lamp bases have to date been standardized in three sizes. The smallest, called the miniature bipin base, is

used on the 6- and 8-watt T-5 lamps.[1] The next base size is the medium bipin base, used on 14-, 15-, 20-, 30-, and 40-watt lamps. The mogul bipin base is the largest and is used on 65- and 100-watt T-17 fluorescent lamps.

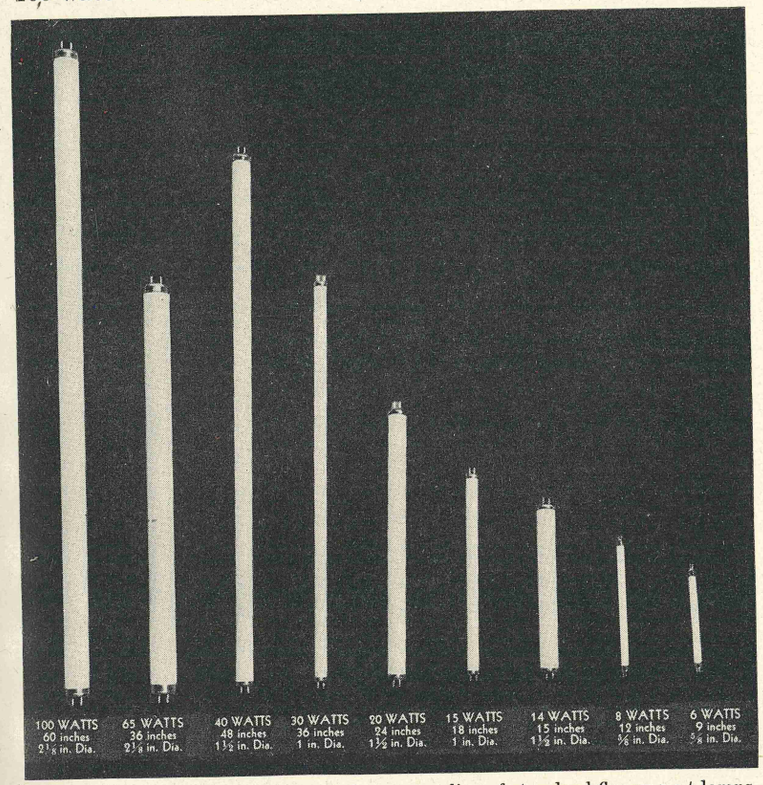


FIG. 1.—The sizes and wattages of the present line of standard fluorescent lamps.

Lamp Construction.—The fluorescent lamp is an "electric-discharge" lamp. Sources producing light by this principle have long been available and are commonplace, although an understanding of their action has never become general knowledge. The Cooper-Hewitt lamp is one such source—in use since 1901. Other familiar electric-discharge sources are neon-sign

[1] The "T" in the bulb designation stands for "tubular," and the number gives the diameter in eighths of an inch. Thus a T-5 lamp would have an approximate diameter of ⅝ in.

tubes, sodium lamps used for street and highway lighting, and mercury lamps of various types employed for industrial illumination, floodlighting, etc.

Figure 2 shows the construction of a modern fluorescent lamp and identifies the component parts. Essentially a glass tube with an electrode sealed in each end, an "arc" is produced by current flowing between those electrodes through mercury vapor contained within the tube when the lamp is connected to the proper power supply. This arc generates *some* visible radiation or light, but *much more* invisible ultraviolet energy which excites fluorescent chemicals coated on the inside of the tube. Unlike

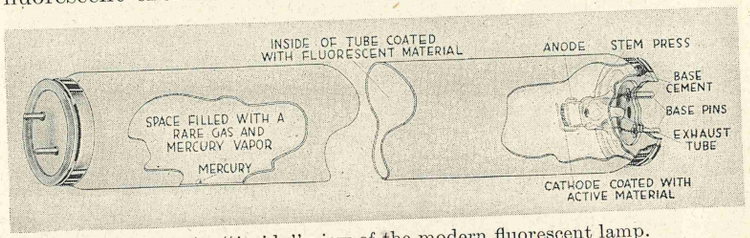


FIG. 2.—An "inside" view of the modern fluorescent lamp.

the ordinary incandescent lamp, the goal of fluorescent lamps is not to produce a maximum of light directly, but rather to generate efficiently short-wave ultraviolet and then employ fluorescent chemicals or "phosphors" which can effectively convert that ultraviolet energy into visible light. It happens that a low-pressure mercury arc produces an abundance of one particular wavelength in this short-wave ultraviolet region, 2537 Å.,[1] and phosphors are selected and blended to respond efficiently at that wavelength.

Although a more complete discussion of fluorescent-lamp operation follows, even the preceding summary will indicate the comparative complexity of this light source. It is complicated when compared with the well-known and simple operation of incandescent filament lamps. Most present-day lighting prac-

[1] An angstrom is about $\frac{4}{1,000,000,000}$ in. Thus energy of 2537 Å. has a wavelength of about $\frac{1}{100,000}$ in. instead of 500 m., which may be the wavelength of the energy emitted by your favorite radio broadcasting station. The eye is simply a receiver tuned to a region of about 3800 to 7200 Å. (see Chap. VIII).

titioners remember the earlier incandescent lamp in which long threads of tungsten were draped up and down inside the bulb, the filament glow and thus the light obviously being a result of the current passing through the tungsten wire. In fluorescent lamps and other electric-discharge sources, current flows between two or more electrodes that have no apparent electrical connection between them. The ramifications of this type of operation are vast and uniquely different from the known and easily predictable characteristics of filament lamps. The following pages indicate the importance of understanding all the related principles of fluorescent-lamp operation so that this source can be utilized to its greatest advantage and the needs of the lighting customer most effectively served.

Some of the early fluorescent lamps were started by applying a relatively high voltage. Once the arc had struck, the current flowed between the electrodes. However, in the present product, the electrodes are preheated before the arc begins; this, in effect, makes it unnecessary to depend on high-voltage bombardment to drive off electrons from the electrodes before the arc starts. These electrons are ultraminute particles of negative electricity which are necessary if current is to flow. Hot materials emit electrons more easily than do cold materials. If the electrodes are cold, several hundred volts are required to make up for the fact that no supply of electrons is present. In either case, the current flow during normal operation heats the electrodes and maintains the electron supply. Although there are many advantages of hot-cathode starting and operation (for example, increased lamp life, greater efficiency, and reduced end blackening), development work is continuing on the higher voltage starting idea (cathodes not preheated), and lamps of such design may come into prominence later.

What Is Inside the Lamp?—Sealed in each end of the fluorescent lamp is an electrode which acts as a terminal for the arc or current flow within the tube. The general term "electrode" refers both to positive and negative terminals, the negative electrode being called the cathode, the positive electrode the anode. Each fluorescent-lamp electrode consists of (1) a coiled-coil tungsten-filament cathode and (2) two antennalike anodes (see Fig. 2). To the cathode is applied an electron-emissive material consisting in this case of barium and strontium oxides.

The cathodes are merely tungsten lamp filaments which can easily be preheated before starting by passing a current through them. The electrons emitted by the hot cathode are "drawn" to the positively charged anode at the other end of the lamp, and current flows through the mercury vapor. During normal operation, the cathodes are kept hot by the electron stream, or "bombardment." The size of the tungsten wire used for cathodes depends on the normal current at which that size of lamp is expected to operate, the wire size being selected so the cathodes for various-sized lamps reach approximately the same temperature. One anode is attached to each of the lead wires that support the tungsten-filament cathode as shown in Fig. 2. Simply remember that the hot cathodes with their coating supply an abundance of electrons to maintain the arc. An intimate knowledge of the electrons is not necessary—fluorescent lamps use them just as radio tubes do.

On alternating-current power systems, the electrode at each end serves alternately as cathode and anode, the current flow being from the electron-emitting tungsten-wire cathode at one end to the antennalike wire anode at the other end. Thus the anode helps preserve the cathode by absorbing the electron bombardment half of the time.

Inside the tube is also placed a tiny drop of mercury and a small amount of argon gas. The mercury weighs only a few milligrams (*i.e.*, a few thousandths of a gram—a gram being $\frac{1}{28}$ ounce). Both mercury and argon are added after the electrodes have been sealed to the tube and the air exhausted. The gas pressure is important; lamps having pressures only slightly greater than called for will give good light output maintenance but are harder to start, whereas, if the pressure is slightly low, the lamps start more easily but depreciate more rapidly in light output. Pressures are closely controlled to effect a compromise. Argon is used to facilitate lamp starting because of the relatively low voltage at which this rare gas can conduct electric current. The initial discharge is through the argon gas, the heat from that arc quickly vaporizing the mercury, and the current is then entirely carried by the mercury vapor.

As has been suggested, the fluorescent lamp like a radio tube is dependent upon a flow of electrons between two electrodes. Mercury vapor is used as the connecting link, the electrical path between electrodes being of relatively low resistance. Thus the discharge or flow of current takes place at comparatively low voltage.

Useful Radiation from the Low-pressure Mercury Arc.—An understanding of the ability of mercury vapor or of any gas or vapor to become "luminescent" or give off light under the influence of the flow of electrons is not a simple one. Technically, the interpretation involves a somewhat complicated treatise on the structure of atoms. Popular explanations of the theory of light production by an electric discharge usually resort to the idea of a "collision" between electrons (speeding from the cathode down the tube toward the anode at the other end) and atoms of mercury vapor with which the tube is filled. This bumping of electrons and atoms is as real in concept as two automobiles colliding on a highway, or as a bowling ball striking a setup of tenpins. The collision displaces electrons of the normal atomic mercury orbit, and radiations of a particular wavelength result as the displaced electrons return to their normal position in the atomic structure; this wavelength depends on the gas used and the degree of electron displacement. The production of light and other radiant energy from the low-pressure mercury arc comes about from the energy given up as the excited particles settle down to their stable or neutral state.

As will be discussed in more detail in Chap. II, auxiliary equipments are necessary to control the current that flows between the two electrodes. This current is called the lamp current, and the voltage drop across the lamp is termed the lamp operating voltage.

A characteristic of the low-pressure mercury discharge is that a considerable portion of the radiant energy is "massed" in single wavelength lines or in very small bands of definite wavelength just as a broadcasting station sends out energy at just one wavelength to which receivers can be tuned. Some of these wavelengths from the mercury arc are in the region that the eye interprets as visible light (see Chap. VIII), but in the case of the fluorescent lamp, much more of the energy is in the far ultraviolet portion of the electromagnetic spectrum. Figure 3 shows that for a tube 1 in. in diameter and consuming 15 watts about 50 per cent of the energy put into the lamp will be converted into 2537 Å. radiation—invisible short-wave ultraviolet energy. The

curve indicates that a still higher percentage can be lumped into this line under very favorable conditions of current density. It

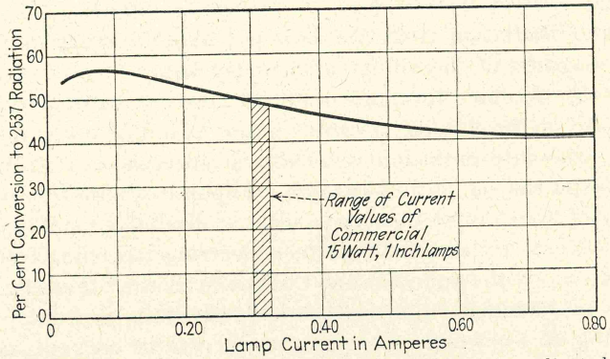


FIG. 3.—The electrical characteristics of a fluorescent lamp are adjusted to give maximum conversion to the short-wave ultraviolet energy needed to excite the fluorescent chemicals with which the tube is coated.

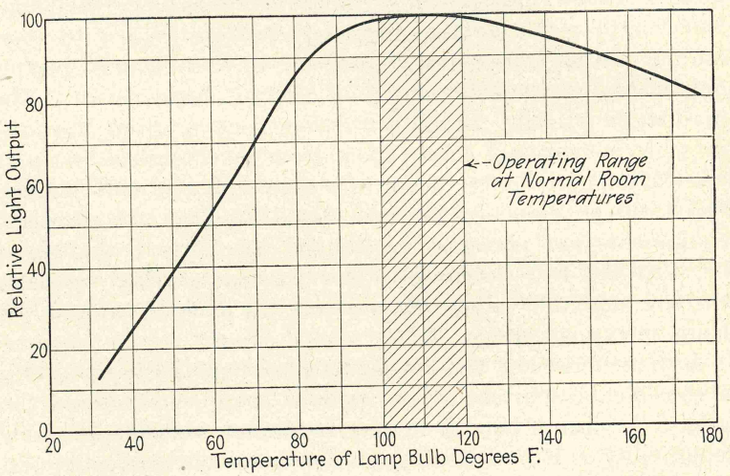


FIG. 4.—This curve shows the effect of one of these characteristics, lamp current, on the conversion to radiation having a wavelength of 2537Å. As shown here, the temperature of the bulb wall is an important factor in the maintenance of conditions for optimum light output.

will be noted that the efficiency of conversion of input energy into 2537 Å. radiation increases somewhat as the current density is decreased. Thus it might be assumed that increasing the bulb diameter while holding the same lamp current would

increase the efficiency. However the gain would be offset by failure to maintain optimum bulb-wall temperature. Figure 4 illustrates the latter effect. If the bulb-wall temperature is too low (either because of low current density or cold ambient temperature), the mercury condenses out and the ultraviolet radiation is reduced. If the bulb temperature is too high, the radiation shifts from 2537 Å. to longer wavelengths because of the increased vapor pressure. There is also increased reabsorption of the 2537 Å. radiation by the vapor.

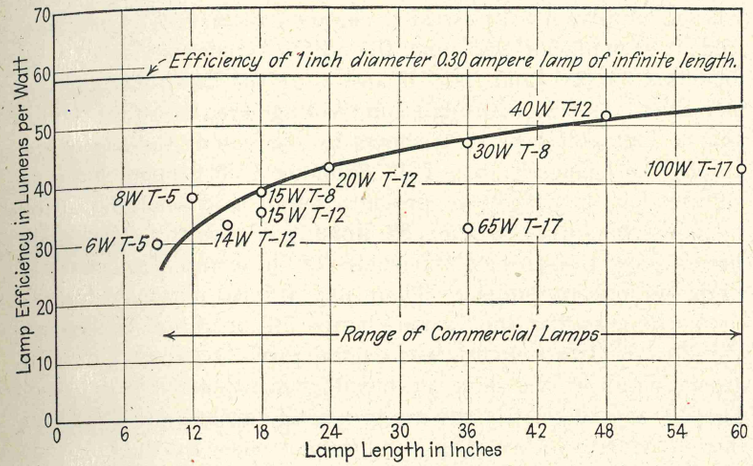


FIG. 5.—The curve indicates how the lamp efficiency varies with lamp lengths for a given loading. The circles show the efficiency of the various sizes of white fluorescent lamps.

The current required to produce a given quantity of light from a fluorescent lamp varies approximately with the square of the inner bulb diameter. This assumes the same surrounding air temperature (known as the "ambient" temperature) and lamp construction.

The remarkable conversion of electrical energy into a single wavelength line actually less than 1 Å. wide and the efficient transformation of this ultraviolet radiation into visible light by the proper selection of the fluorescent chemicals coated within the tube explain the phenomenal efficiency of fluorescent lamps. In contrast, a 300-watt standard filament lamp emits only about 11 per cent of its input wattage within the visible

spectrum as light, and this radiation is spread throughout the visible spectrum ranging from about 3800 to 7200 Å.

The length of the tube also influences the relative efficiency as shown in Fig. 5. The curve of this graph shows the efficiencies of various lengths of 1-in. diameter white fluorescent lamps operating at 0.30 ampere (the rated current of the standard 15-watt 1-in. diameter fluorescent lamp). There is a somewhat constant loss owing to the fixed voltage drop at the electrodes—somewhere between 12 and 18 volts depending upon the electrode size, cathode emission, and filling gas. This electrode voltage drop represents wasted energy for the most part, but, since it is somewhat constant, the efficiency for a given loading[1] increases as the lamp length and thus the lamp voltage are increased. Lamps with high lamp voltage are, therefore, favorable to high efficiency. As shown by the line at the top of the graph, the efficiency of a 1-in. diameter 0.30 ampere lamp of infinite length based on present design and manufacturing methods would be around 58 lumens per watt. The small circles show the present efficiencies of the commercial sizes of white fluorescent lamps.[2] There are definite reasons why the circles representing the various lamps fall on or off the curve. The 30-watt lamp almost falls on the curve because its current density is about the same as that on which the curve is based. The 20- and 40-watt lamps are practically on because the lower current density (a favorable condition) is offset by the fact that (1) the bulb-wall temperature falls below the optimum and (2) the proportion of input energy used to produce fluorescence is less because the lamp voltage is lower than that of corresponding

[1] The commonly used indication of loading is the factor "watts per square inch of lighted surface." This factor is 0.28 for the 15- and 30-watt T-8 lamps, 0.19 for the 20-watt lamp, 0.18 for the 40-watt, 0.30 for the 65-watt, and 0.26 for the 100-watt lamp. For intended ambient temperatures of 80°F., the practical loading factor range is 0.15 to 0.30 watts per sq. in. of lighted surface. The lamp cost per unit of light output is too high if the loading factor is below 0.15, and above 0.30 the lamp efficiency is low and the light output depreciation rapid. A study of Fig. 5 shows this to be true.

Since more wattage is available for maintaining the bulb-wall temperature, lamps with high loading factors would be desirable for operation in low ambient temperatures. The converse would hold for high ambient temperature operation.

[2] As of December, 1941.

lengths in 1-in. diameter. The 14-watt T-12 lamp falls below the curve because it is in the range where the electrode drop becomes more important. The 65- and 100-watt T-17 lamps are less efficient than 1-in. lamps of the same length chiefly because the former have a much lower lamp voltage. The converse is true of the 6- and 8-watt T-5 lamps. Tabulated efficiency values in lumens per watt will be found in Table 4.

Phosphors Convert the Ultraviolet Energy into Visible Light.—It will be evident at this point that, if the energy lumped into the 2537 Å. line by the low-pressure mercury discharge can be used to efficiently excite fluorescent chemicals, the result will be a light source whose output of visible radiation per watt of input power far exceeds anything from an incandescent filament source. That is exactly what happens. Table 1 shows what

TABLE 1.—TYPICAL PHOSPHORS

Phosphor	General color	Exciting range,* angstroms	Sensitivity peak, angstroms	Emitted range, angstroms	Emitted peak, angstroms
Calcium tungstate.....	Blue	2200–3000	2720	3800–7000	4400
Magnesium tungstate..	Blue-white	2200–3200	2850	3800–7200	4800
Zinc silicate.....	Green	2200–2960	2537	4500–6200	5250
Zinc beryllium silicate.	Yellow-white	2200–3000	2537	4500–7200	5950
Cadmium silicate.....	Yellow-pink	2200–3200	2400	4300–7200	5950
Cadmium borate.....	Pink	2200–3600	2500	4000–7200	6150

* 2200 Å. is lower limit of measurements.

chemicals are used to produce various colors of light, their exciting range and their emitting range. Figure 6 shows the sensitivity of one of the chemicals, zinc silicate, to exciting radiations of various wavelengths. Note that the sensitivity of this particular phosphor is almost a maximum at the 2537 Å. wavelength point which the vapor discharge produces so abundantly within the tube. However, the phosphors used do not all have the same sensitivity as shown in Fig. 6. This fact, plus their different characteristics as regards the distribution of energy in the visible spectrum, explains why all colors do not have the same efficiency. For example, the 3500° white phosphor is more efficient than the 6500° daylight. Actually, whenever

possible, phosphors have been selected with their maximum sensitivity between 2500 and 2600 Å., because no other ultraviolet line of the low-pressure discharge in the fluorescent lamp has as much as 4 per cent of the energy found in the 2537 line. The explanation of how a fluorescent chemical or phosphor transforms invisible ultraviolet energy into visible light introduces even more complications than those involved in the interpretation of the production of light and radiant energy by sheer electronic activity within an electric discharge source. A simple explanation of the former phenomena is that the phosphors absorb energy at one wavelength and reradiate it at longer wavelengths in much the same manner as a transformer absorbs wattage at one voltage and current, delivering the power at a different voltage and current. However, the energy reradiated by the fluorescent chemicals is spread over a considerable range or continuous band of visible wavelengths. Much laboratory effort has been spent in studying the behavior of chemicals of different composition and purity in the search for phosphors that yield the most visible light under the influence of the ultraviolet radiation at 2537 Å. which a lamp of the present type produces so efficiently. The logic will be apparent of establishing first the best possible source of that radiation as far as the electrical and mechanical characteristics are concerned and then keying phosphors to this source by chemical science.

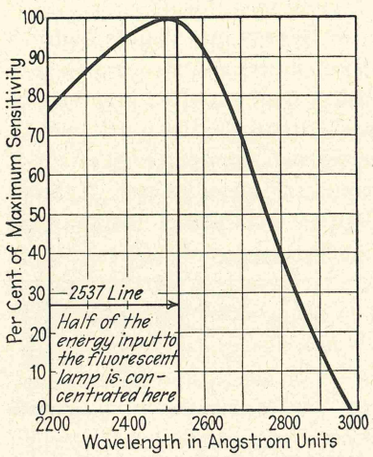


FIG. 6.—Fluorescent-lamp phosphors are not equally responsive to all wavelengths. The above curve is for zinc silicate whose maximum sensitivity is very near the 2537Å wavelength produced so efficiently within the fluorescent lamp. This is one of the reasons why the green lamp is more efficient than any of the other colors.

The actual phosphors used are not the chemically pure compounds mentioned in Table 1. Some impurity or "activator" is required to produce fluorescence of the desired character. The treatment of the phosphor in the various manufacturing processes also has considerable influence on the emitted radiation. Mixtures of phosphors are also used, the coating inside the white fluorescent lamp being a mixture of two phosphors.

All fluorescent lamps are white when not lighted except the gold and red lamps which have an inner coating of pigment to filter the light and leave the desired color.

Conversion of Energy within a Fluorescent Lamp.—Figure 7 shows graphically how the 40 watts of input energy to the standard 48-in. fluorescent lamp is converted within the tube and ultimately distributed. It will be noted that a little over 2 per cent (0.9 watts) goes directly into the production of light by the mercury discharge. Fifty-five per cent is converted into ultraviolet energy concentrated at the 2537 Å. line, and 43 per cent, or a little over 17 watts, appears within the lamp as heat and serves to keep electrodes and bulb warm. The lower bar shows the ultimate nature of the energy output with 6.5 of the 22 watts of ultraviolet energy being transformed by the fluorescent powders into visible light, whereas the remainder is lost as heat. The latter, combined with the 17 watts previously mentioned, is finally dissipated in the form of radiant infrared energy (which accompanies the light but is manifested as heat only) and by convection and conduction (dissipated by heating the surrounding air and by convection to fixture parts).

The region marked "light" represents the proportion of radiant energy in the visible spectrum. The color quality and the actual light output as measured in lumens will, of course, depend upon the distribution of the energy within the visible spectrum. This, in turn, depends upon the composition and blending of the phosphor itself.[1]

Radiant Heating Effects.—It should be noted from Fig. 7 that only about one-fourth of the lamp wattage actually accompanies the light as infrared radiant heat. This is the radiation that gives the sensation of heat, for, although the wavelength is too long to be appraised as light by the human seeing organ, it does produce heat when it strikes and is absorbed by some material.

Fluorescent lamps produce cooler footcandles than do incandescent filament lamps. Although a kilowatt-hour represents an over-all heating effect of 3414 B.t.u. regardless of how that energy is consumed, the lesser sensation of heat from fluorescent lamps

[1] See Chap. VIII.

lies in the fact that only 25 to 35 per cent of the energy is radiated in the infrared region as compared with 60 to 75 per cent for gas-

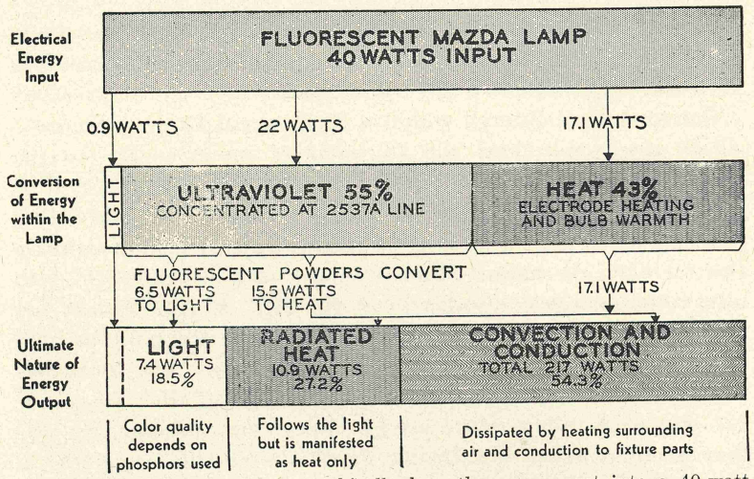


FIG. 7.—This chart shows graphically how the energy put into a 40-watt fluorescent is (1) converted into short-wave ultraviolet energy, and (2) ultimately distributed as visible light, radiant heat, and conduction and convection.

filled tungsten-filament lamps. Because (1) the efficiency of light production by fluorescent lamps is about double that of filament lamps and (2) since the infrared heat radiated is only

TABLE 2.—RELATIVE HEATING EFFECT PER FOOTCANDLE

	Approximate Relative Radiant Energy per Footcandle
40-watt white fluorescent lamp	1.0
40-watt daylight fluorescent lamp	1.25
40-watt tungsten-filament lamp	6.6
100-watt tungsten-filament lamp	5.7
200-watt tungsten-filament lamp	5.1
500-watt tungsten-filament lamp	4.5
Sunlight through open window	1.25
Sunlight through ⅛-in. glass window	1.04
Skylight through ⅛-in. glass window	0.67
40-watt fluorescent lamp through ⅛-in. ordinary glass	0.44

half that of filament lamps, the statement is commonly made that the sensation of heat from fluorescent lamps is, roughly, only one-quarter that from filament lamps for the same amount

of light delivered. Thus the fluorescent lamp obviously has a considerable advantage wherever low infrared radiation is of importance.

Table 2 shows the infrared energy per footcandle for various light sources.

"Cold" Light.—The term "cold" light technically means that a lamp uses all its input energy in producing light, *i.e.*, radiation within the visible spectrum. Although the fluorescent lamp is commonly referred to as producing cold light, actually it should be spoken of as being more nearly a cold light than the tungsten-filament lamp. Figure 4 showed that the relative efficiency is highest when the bulb temperature is around 100 to 120°F., *i.e.*, at normal room temperature of 70 to 80°F. In such a case, the bulb-wall temperature would be only 30 to 40°F. hotter than the normal room temperature and to that extent might be called a cold light.

Available Colors.—Many of the fluorescent lamps are available in eight colors, *viz.*, daylight, white, soft white, blue, green, pink, gold, and red. The daylight lamp has a color temperature of 6500°K., which is the recognized standard value of "white" light and represents the color quality of light coming from overcast outdoor skylight. A complete discussion of its color-matching qualities will be found in Chap. VIII. The white lamp has a rated color temperature value of 3500°K., which means that the color quality of its light is more nearly comparable to incandescent filament lamps (the color temperature of a 500-watt filament lamp is about 3000°K.). The soft-white lamp has a greater proportion of pink.

One of the important advantages of the fluorescent light source is the ability to produce color directly, and the availability of highly efficient colored lamps has opened up an entirely new realm for the decorator, architect, and display man. In the blue, the green, and the pink lamp, the phosphors transform the ultraviolet energy directly into visible light of those colors. In the case of the gold and red lamps, an additional coating of colored pigment is applied between the phosphor and the inner surface of the tube since it is not possible to obtain the desired shade by phosphors alone.

The efficiency of colored fluorescent lamps as compared with coated or natural-colored bulb filament lamps illustrates the

TABLE 3.—DIMENSIONS AND ELECTRICAL DATA*

Lamp watts†	6	8	14	15(T-8)	15(T-12)	20	30	40‡	65	100
Nominal length, inches	9	12	15	18	18	24	36	48	36	60
Diameter, inches	5/8	5/8	1½	1	1½	1½	1	1½	2⅛	2⅛
Bulb	T-5	T-5	T-12	T-8	T-12	T-12	T-8	T-12	T-17	T-17
Approximate lamp amperes	0.15	0.18	0.37	0.30	0.33	0.35	0.34	0.41	1.35	1.45
Approximate lamp volts	45	54	41	56	48	62	103	108	50	72
Circuit voltages	110–125	110–125	110–125§	110–125	110–125	110–125	199–216 220–250 110–125	199–216 220–250 110–125	110–125	199–216 220–250 110–125
Rated average life, hours‖	1000	1000	1500	2500	2500	2500	2500	2500	2000	3000

* As of February, 1942.

† Add auxiliary watts for total.

‡ A 40-watt fluorescent lamp specially designed for low-temperature starting is also available. It gives proper starting down to 0°F. and has a present estimated life of 1500 hr. While these lamps will operate at normal room temperatures, they should not be used for general service because of their poor lumen maintenance and shorter life.

§ For two-in-series operation in which a specially designed filament lamp (60 volts, ½ ampere, S-11 outside-white bulb, intermediate-screw base) is used as a resistance ballast. Total wattage of two lamps and ballast is 45 on alternating current, 38 on direct current.

‖ Under specified test conditions.

remarkable advantages of producing color directly instead of by subtracting the desired color from the entire visible spectrum. In certain comparisons, the fluorescent lamp is many times as efficient as the filament lamp of the same color. However, for the fluorescent lamp colors commonly employed for general lighting, the efficiency advantage over the higher wattage filament lamps is only two or two and one-half times.

The benefit to the public of this efficiency gain can be realized by remembering that America's electric bill for lighting is around one billion dollars annually. An improvement in efficiency of even 1 per cent represents a bonus of $10,000,000 of light to customers. The 100 per cent boost in efficiency of fluorescent over filament lamps, even though in the minority as regards numbers used, gives the public an appreciably greater amount of light for the money.

Dimensions and Electrical Data.—Table 3 gives the commonly needed dimensions and electrical data on the 10 present standard sizes of fluorescent lamps. The nominal lengths tabulated include one lamp and two lampholders and thus indicate the length that each lamp will require in application. The actual over-all length including the base pins is, for example, $47\frac{25}{32}$ in. for the 40-watt 48-in. lamp. The nominal lengths are obviously of more value since they indicate the spacing on centers of continuous rows of lamps.

The circuit voltages listed in the table are based on the rated voltage range of ballasts available for fluorescent lamps. The lamp volts is the total voltage across the lamp and is usually about 3 volts higher than the arc volts. This difference is due to the cathode resistance and depends on the distance of the "hot spot" of the arc from the line side of the cathode lead-wire connection.

Lumen Outputs.—The lumen is the common measure of the quantity of light.[1] Table 4 shows the lumen output and lumens per watt efficiency of the standard sizes and colors of fluorescent lamps. These lumen output ratings apply at the end of 100 hr. of operation, the initial lumen output being about 10 per cent higher than this 100-hr. value.[2]

[1] Technically the rate of flow of light.

[2] See Chap. V.

TABLE 4.—LUMEN OUTPUTS AND LAMP LUMENS PER WATT*

Lamp watts	6	8	14	15(T-8)	15(T-12)	20	30	40	65	100
White	180	300	475(34)	585(39)	525(35)	860(43)	1450(48)	2100(52)	2100	4200(42)
Daylight	155	250	390(28)	525(35)	450(30)	760(38)	1300(43)	1800(45)	1800	3700(37)
Soft white	...	...	320(23)	435(29)	400(26.5)	640(32)	1100(37)	1500(37)	....	2950(29.5)
Blue	...	...	.....	315	285	460	780			
Green	...	...	.....	900	810	1300	2250			
Pink	...	...	.....	300	270	440	750			
Gold	...	...	.....	375	335	540	930			
Red	...	...	.....	45	40	60	120			

* Lumen output and efficiency ratings apply at the end of 100 hr. of operation. The efficiency of daylight and white fluorescent lamps at 70 per cent of rated life is about 85 per cent of initial rating. (Lumen output and efficiency data as of February, 1942.)

TABLE 5.—MAXIMUM BRIGHTNESS IN FOOTLAMBERTS AND CANDLES PER SQUARE INCH*

Lamp watts	6	8	14	15(T-8)	15(T-12)	20	30	40	65	100
White	2450(5.42)	2440(5.40)	1340(2.92)	2040(4.52)	1400(3.10)	1580(3.49)	2480(5.49)	1750(3.87)	1530(3.38)	2180(4.82)
Daylight	2100(4.65)	2030(4.49)	1100(2.43)	1830(4.05)	1200(2.65)	1400(3.10)	2220(4.90)	1500(3.32)	1310(2.90)	1920(4.25)
Soft white	.....	.....	920(2.04)	1550(3.43)	1070(2.36)	1200(2.65)	1890(4.17)	1250(2.77)	.....	1530(3.38)
Blue	.....	.....	.....	1125(2.49)	750(1.66)	850(1.88)	1350(2.99)			
Green	.....	.....	.....	3200(7.08)	2160(4.78)	2400(5.31)	3900(8.63)			
Pink	.....	.....	.....	1050(2.32)	720(1.59)	800(1.77)	1300(2.88)			
Gold	.....	.....	.....	1650(3.65)	900(1.99)	1000(2.21)	1600(3.54)			
Red	.....	.....	.....	160(0.35)	110(0.24)	110(0.24)	210(0.46)			

* As of February, 1942. Maximum values at center of lamp perpendicular to the lamp. 1 candle per square inch = 452 footlamberts.

Fluorescent Lamp Brightnesses.—Table 5 gives the maximum brightness in footlamberts and candles per square inch for the present line of fluorescent lamps. This maximum brightness is measured at the center of the lamp and perpendicular to the lamp. The average brightness is about 75 to 80 per cent of the

FIG. 8.—The 85-watt type RF lamp (bottom) shown in comparison with the familiar 40-watt standard fluorescent lamp.

maximum values shown in the table. However, the acceptability of a fluorescent lighting system from the comfort standpoint must in most cases be appraised on the basis of maximum brightness.

The footlambert is the brightness unit now in widest use in modern lighting nomenclature. Brightnesses in candles per square inch have also been included in the table for the benefit of

FIG. 9.—A close-up view showing the base construction and prongs of the type RF lamp.

older lighting men whose brightness concepts are based on this unit. One candle per square inch is equal to 452 footlamberts.

The Type RF Lamp.—Another fluorescent light source is the 85-watt type RF lamp (Fig. 8), which operates from specially designed auxiliary equipment different from those used with standard fluorescent lamps. RF lamps are 58 in. long, 1¼ in. in diameter, and have special bases that do not fit ordinary fluorescent lampholders (Fig. 9).

Development work on both the RF lamp and the standard fluorescent lamp began about the same time, and these two light sources are similar in many ways. Of most importance, both are low-pressure mercury arc sources, depending upon the activation of fluorescent phosphors for the production of light.

The letters RF stand for "rectified fluorescent," the lamp being so named because it is self-rectifying, *i.e.*, the current flows

in only one direction through the tube. Available in two colors designated as "blue-white" and "industrial-white," the lamps produce 4000 lumens initially and have an average rated life of 3000 hr. The details of the auxiliary circuit and the discussion of RF lamp operation will be found in Chaps. II and III.

New Lamp Sizes.—Since there are so many factors that influence lamp performance—length, current density, sensitivity of phosphors, bulb-wall temperature, etc.—it has not been easy to select lamp dimensions and electrical characteristics. Not only must conditions be selected that produce maximum luminous efficiency, but numerous other factors must be weighed in their true perspective. These include adaptability to starting and operating on standard line voltages, suitable voltage drop, minimum wattage loss in ballast equipment, esthetically pleasing proportions, low surface brightnesses, and commercial adaptability to manufacture, shipment, and use. New possible sizes must all be appraised in the light of these various factors.

CHAPTER II

AUXILIARY EQUIPMENT

Why Auxiliary Equipment?—There are two fundamental reasons why it is necessary to provide auxiliary equipment for fluorescent-lamp operation. These are as follows:

1. To limit the lamp current because of the inherent negative-resistance characteristic of all electric-discharge sources.
2. For "low-voltage" operation, some method must be provided for preheating the cathodes and initiating the discharge.

This "negative-resistance" characteristic of fluorescent lamps means that the voltage drop across the lamp *decreases* as the arc current goes up. The reverse is true in the case of the tungsten-filament lamp and of most other resistance normally encountered in electrical work. Ohm's law (voltage = current times resistance) simply does not apply to the fluorescent lamp, and therefore it is necessary to use auxiliary ballast equipment that will hold the current constant and thus protect the lamp from line-voltage changes. Without a device to provide this protection, an increase in line voltage would increase the arc current, and this, in turn, would lower the arc voltage and result in a still further increase in current through the arc. This process would continue until the lamp was destroyed.

Several advantages of preheated-cathode starting of the low-pressure mercury arc were mentioned in Chap. I. An important one is that relatively low lamp voltages can be employed giving the greatest amount of safety in operation and ease of replacement. Preheated-cathode starting and hot-cathode operation also result in improved lumen maintenance throughout life and more efficient production of the short-wave ultraviolet radiation which excites the fluorescent chemicals.

The Simple Fluorescent Circuit.—The simple fluorescent circuit consists of (1) a ballast to limit the arc current and (2) a starting switch which momentarily closes and then opens the cathode heating circuit. The simple connections are shown in Fig. 10, the starting switch in this case being a knife switch.

Each lamp requires a separate starter and a separate ballast, although two ballasts for twin-lamp operation may be contained within a single case. Specifically designed auxiliary equipments are required for each wattage size, for each frequency, and for each voltage range.

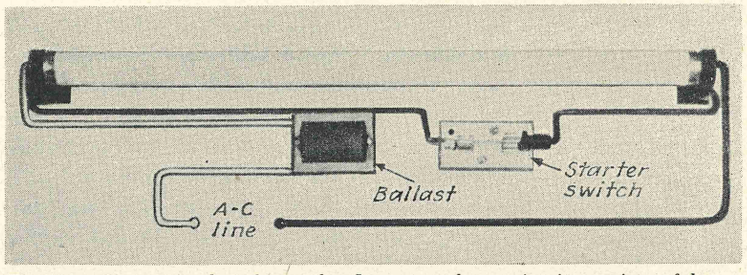


FIG. 10.—In its simplest form, the fluorescent-lamp circuit consists of lamp, ballast, and a starter switch, as shown.

The Ballast Choke.—The fluorescent-lamp ballast consists of iron-core choke coil whose physical dimensions and electrical characteristics are determined by the lamp, frequency, and voltage for which it is designed and by the ballast wattage loss considered acceptable for the service. A resistance ballast could be employed instead of an inductive choke coil, but the energy loss in the resistance would be equal to or greater than the lamp watts and so the over-all efficiency of light production would be lower.[1] There is, however, a further advantage for using an iron-core inductive choke as a ballast.

The discharge within a fluorescent lamp will not start at all on the voltage furnished by a 110–125 volt alternating-current supply. The peak voltage of such a supply voltage is still insufficient to break down the tube resistance and start the arc. However, after the starting switch has been closed for the brief interval necessary to preheat the cathodes sufficiently and then either manually or automatically opened, an "inductive kick" from the ballast supplies a momentary voltage high enough to start the lamp. This inductive kick results from the inherent characteristic of all inductances to resist any changes in current

[1] The series circuit for two 14-watt 15-in. lamps discussed later in this chapter is actually a compromise between the low ballast loss (choke-coil system) and high power factor (resistance-ballast system).

flow. Hence, when the circuit is opened by the starting switch, a voltage of its own or "counterelectromotive force" is developed by the ballast which attempts to continue the current flow. As mentioned, this surge of voltage is usually sufficient to start the lamp.

After the discharge has started, the ballast limits the arc current to the value for which the lamp was designed. This current-limiting function arises out of the fact that as the arc tries to draw more current (for example, because of a momentary line voltage boost) a higher voltage drop will be used by the ballast, leaving less of the supply voltage available at the lamp. Therefore the lamp current will be reduced to its nominal value. Thus the ballast keeps the circuit from becoming over-balanced. The heat from the discharge itself keeps the cathodes hot during normal operation, hence the starter switch can remain open.

A well-designed ballast should

1. Provide sufficiently high starting current to preheat adequately the lamp cathodes.
2. Have the correct characteristics so that the lamp operates at its normal voltage and wattage.
3. Have good regulation so that current-limiting control is not destroyed by line-voltage fluctuations.
4. Have a reasonably low wattage loss.
5. Have satisfactory operating temperature.
6. Have low noise level.

The Starting Switch.—Because the manual type of starting switch is inconvenient and impractical for installations involving a large number of lamps, several types of automatic starting switches have been developed. All such switches, or "starters," provide first for cathode preheating and then promptly open the circuit so that the inductive kick can start the lamp. The first of these was a magnetic switch which consisted of a simple "doorbell" type of magnetic contactor. The vibrator element was so constructed and connected that the cathode heating circuit was repeatedly opened and closed, the cathode gaining heat at each contact until the discharge started. The operating current then produced a field of sufficient magnitude in the electromagnet operating the vibrator element to hold the contacts open. Although the magnetic switch resulted in quick

and positive starting, it consumed 1 or 2 watts during normal lamp operation (the energy necessary to hold the contacts open) and its many moving parts made it susceptible to trouble.

A thermal switch was then developed. It was constructed and wired so that the normal preheating current flowing through the lamp cathodes also passed through a small heater coil in the

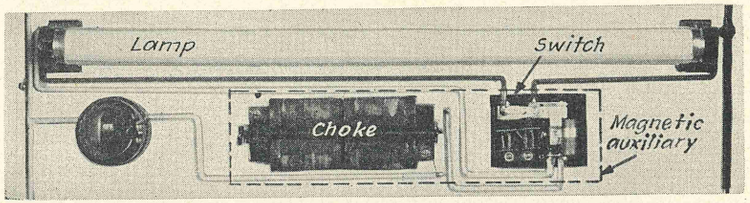


FIG. 11.—The component parts of the magnetic auxiliary circuit.

starting switch, the heat from this coil actuating a bimetallic strip on which the contacts were mounted. The design was very similar to that shown for the replaceable thermal type of starter (Fig. 20). The thermal type of switch like a flasher button obviously requires some slight delay in restarting, for the heat from the coil which holds the contacts open during normal lamp operation must be dissipated before the contacts close and

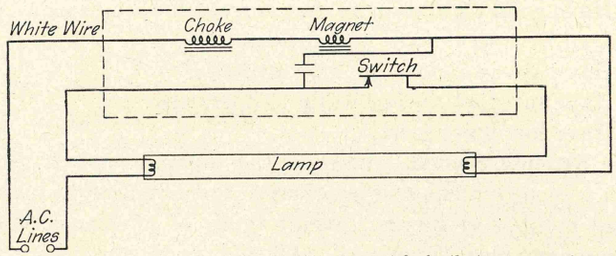


FIG. 12.—The wiring diagram for auxiliaries with built-in magnetic switches.

the starting cycle is repeated. Several seconds are usually required for the contacts to close before restarting.

Auxiliaries with Built-in Starting Switches.—The early fluorescent-lamp auxiliaries had both starting switch and ballast choke in the same case. One type, called the magnetic auxiliary, used a built-in magnetic switch of the type described above. The component parts of such an auxiliary and their relation to the fluorescent-lamp circuit are shown in Fig. 11. The wiring diagram is given in Fig. 12. The other type was the thermal

auxiliary which contained a choke and thermal switch in a single case, as shown in Fig. 13. Thermal auxiliaries were wired as shown in Fig. 14.

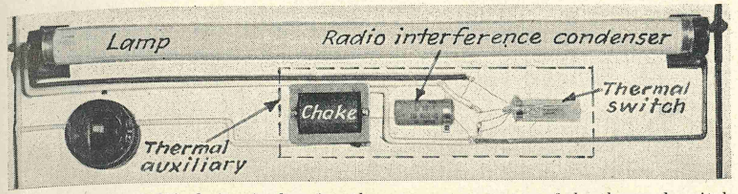


FIG. 13.—A simplified circuit showing the component parts of the thermal-switch auxiliary.

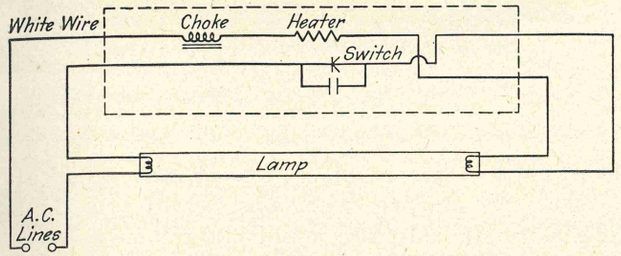


FIG. 14.—The wiring diagram for auxiliaries with built-in thermal switches.

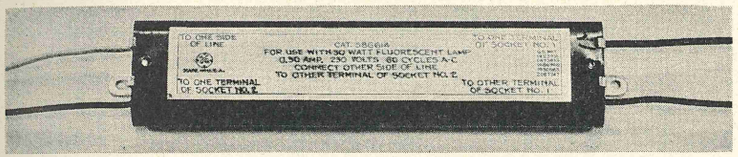


FIG. 15.—A typical magnetic auxiliary.

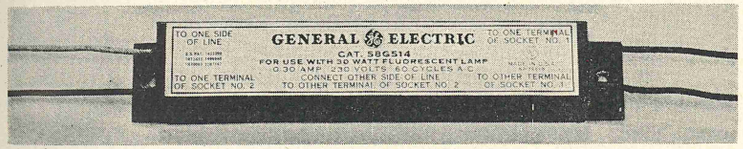


FIG. 16.—A typical thermal auxiliary.

The larger quick-starting magnetic switch was combined with a bigger, low-loss choke in the magnetic auxiliary, whereas the compact thermal switch was combined with the small, cheaper choke in the thermal auxiliary. Thus the magnetic auxiliary was the more expensive of the two but had a lower energy loss. Figure 15 shows a typical magnetic-switch auxiliary, and Figs. 16

and 17 outside and inside views of a thermal auxiliary. Auxiliaries with built-in switches are no longer listed on standard fluorescent-ballast schedules.

Replaceable Starters.—The moving parts of the automatic starting switch make it the element in the fluorescent circuit

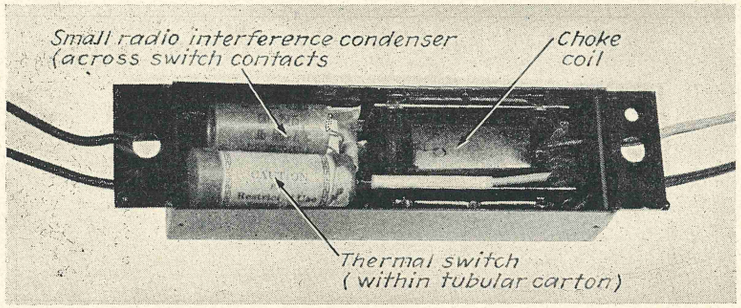


FIG. 17.—An inside view of a typical auxiliary with built-in thermal switch.

most likely to cause trouble, either by breakage in shipment or by usage. When the starting switch was located with the ballast choke inside the auxiliary case, a faulty switch meant tearing up the wireway and replacing the complete auxiliary. To help overcome this trouble, the choke and the starting switch were made separate and individual parts. The result was the fluorescent-lamp ballast and the replaceable starter.

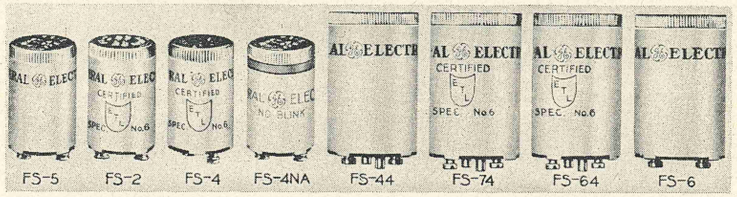


FIG. 18.—The present fluorescent starter line.

Whereas many variations of automatic and replaceable starting switches are possible, the two types in widest use today are the glow-switch starter and the thermal-switch starter. Figure 18 shows the size and shape of the present line of starters. Table 6 indicates the lamp sizes for which each starter is designed and the type of switch used in each.

Glow-switch Starters.—Figure 19 shows the internal elements of the glow-switch starter. The switch assembly is contained

within the small glass bulb and consists essentially of a center vertical electrode or fixed contact and a U-shaped bimetallic strip or movable contact. The bulb is filled with neon, helium, or argon, depending on the lamp size for which the starter is designed. A small radio-interference condenser is connected across the switch.

TABLE 6.—FLUORESCENT STARTERS

Starter designation	FS-5	FS-2	FS-4	FS-4NA	FS-44	FS-74	FS-64	FS-6
Lamp watts	6 8	15 20	30 40	40	40	65	100	100*
Type of switch	Glow	Glow	Glow	Glow	Thermal	Thermal	Thermal	Glow*
Number of terminals	2	2	2	2	4	4	4	2*

* For replacement in two-terminal starter sockets for 100-watt lamps.

All glow-switch starters have two terminals, connected to each side of the lamp as shown. On starting, when there is practically no voltage drop at the ballast, the voltage at the starter is sufficient to produce a glow discharge between the U-shaped

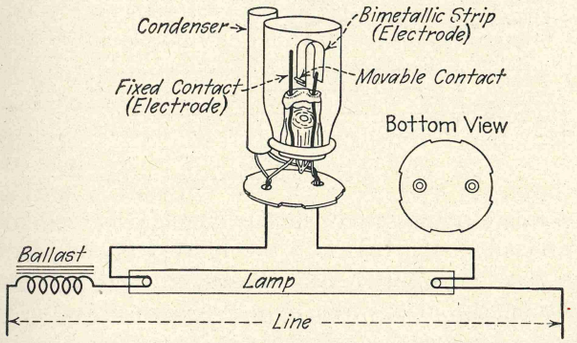


FIG. 19.—The construction details of the glow-switch type of fluorescent starter.

bimetallic strip and the fixed contact or center electrode. The switch performs like an ordinary glow lamp in this respect. Then the heat from the glow moves the free end of the bimetal to the center vertical electrode and the contacts close. This places the lamp cathodes and the ballast in series across the line, and the lamp cathode preheating begins.

When the switch contacts close, the glow discharge in the starter is shorted out and the bimetal cools. After a very short

time (during which the lamp cathodes become preheated), the contacts open. Then, as previously described, the ballast (like all inductances) resists the attempt to stop the current flow by generating a voltage of its own, called the "inductive kick," which is usually sufficient to start the fluorescent lamp. After the lamp starts, about one-half the available voltage (the line voltage in the case of simple series choke ballasts and the secondary voltage in the case of autotransformer types of ballasts) is consumed at the ballast, so the voltage at the lamp and thus at the starter is insufficient to produce further glow. Therefore the contacts remain open and the starter consumes no energy during lamp operation.

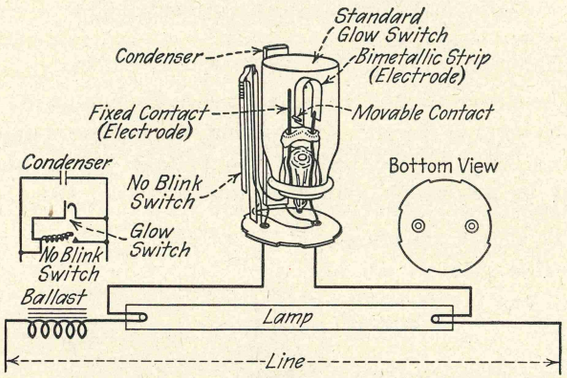


FIG. 19A.—A No-Blink fluorescent starter.

Two-terminal glow-switch starters simplify fluorescent circuit wiring and allow the ballast to be located at any convenient distance from the lamp. Although rugged and inexpensive to manufacture, the glow-switch is a "voltage-activated" device and must be designed to glow on the voltage available across the lamp terminals. But it *must not* glow during normal lamp operation when the available voltage may be only 30 to 50 volts less than the starting voltage. Too, the lamp voltage is by no means constant but is changed by the surrounding or ambient temperature in which the lamp is operated, by the supply voltage, etc. Individual lamps also have some variation in lamp volts. For these reasons, it is difficult to meet the requirement that a glow switch will not close or "reglow" on the voltage developed by the lamp discharge.

Newest of glow-switch starters is the "No-Blink" starter, FS-4NA. Designed to operate 40-watt fluorescent lamps, the FS-4NA is interchangeable with the present FS-4 starter. The new device consists of a standard glow switch in series with a thermal element as shown in Fig. 19*A*. During normal starting when the lamp is still operative, the glow switch functions in the fashion above described. But when the lamp becomes deactivated and the glow switch makes repeated efforts to start it, the thermal element or "No-Blink switch" becomes heated and automatically short-circuits the glow switch, thus eliminating any further attempts to start the lamp. The No-Blink element operates after approximately 15 to 20 sec. at rated line voltage, after which the lamp cathodes remain heated until the lamp is replaced or the power turned off. When a new lamp is installed the starter assumes its normal function and the No-Blink switch remains open until repeated blinking occurs again.

Sometimes the question arises as to the possibility of substituting glow starters for built-in switches of thermal or magnetic auxiliaries which have failed. It will be noted by examining the circuit of such auxiliaries that if the heater or magnet coil of the switch is the element at fault, the choke-coil circuit is internally broken and a new ballast and starter will be required. If the heater coil remains intact and the switch contacts fail to operate, it is possible to add a glow starter across the proper lamp terminals in the conventional manner. Such a procedure is at the most makeshift. The replacement of the failed built-in switch auxiliary with a ballast and starter would be more practical in most cases.

Thermal-switch Starters.—Four-terminal thermal-switch starters have been developed for 40-, 65-, and 100-watt fluorescent lamps. The construction and connection to the circuits are illustrated in Fig. 20. The switches in these starters consist of two bimetallic strips and a filament type of heater coil. They are similar to those employed in early thermal auxiliaries with built-in switches.

Of the four terminals on thermal-switch starters, the two larger ones (*A* and *D*) go to the two bimetallic strip contacts, and the two smaller ones (*B* and *C*) to the starter heating element. On starting, the ballast, starter heating element, and lamp cathodes are all in series across the line since the starter contacts

are normally closed. Thus the current that preheats the lamp cathodes also heats the U-shaped bimetallic strip, which soon moves away from the vertical strip and opens the contacts. Then the inductive kick from the ballast starts the lamp and the normal lamp operating current flows through the starter heating element and produces enough heat on the U-shaped bimetallic strip to hold the contacts open.

Although four-terminal thermal-switch starters have a small wattage consumption during normal lamp operation, their

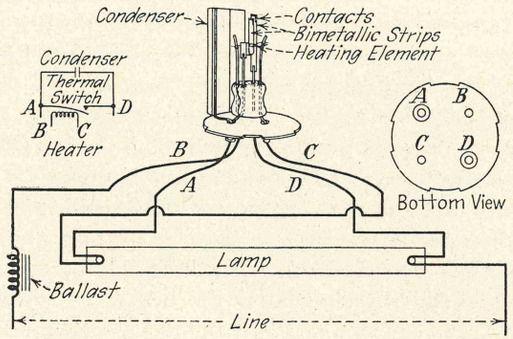


FIG. 20.—Details of the four-terminal thermal-switch fluorescent starter.

design insures more positive starting by providing (1) an adequate preheating period, (2) a higher induced starting voltage, and (3) characteristics inherently less susceptible to line-voltage variations.

The FS-44 thermal-switch starter gives the best all-round performance of 40-watt lamps and is especially useful under such adverse conditions as direct-current operation,[1] low temperature, varying voltage, etc. As mentioned previously, the thermal-switch principle results in more nearly ideal starting conditions, and therefore greater lamp life from the standpoints of adequate preheat and more positive starting and restarting. Because of its size and the fact that it has four terminals, the FS-44 is not interchangeable with the FS-4 starter.

Owing to the different characteristics of various sized lamps, starters must be designed to meet particular requirements. The glow-switch design is more appropriate for some sizes of lamps, the thermal switch for others. It is possible, however, that new

[1] See Chap. III for precautions to be observed.

starting devices and techniques may change the whole starter situation in the future.

All automatic starting switches should (1) have satisfactory starting and restarting time characteristics, (2) have a reasonable service life, (3) provide adequate cathode preheating, and (4) start a lamp even at relatively low ambient temperatures. The starter operation largely controls the lamp life, and the quality of the start is equally as important as the number of starts. In addition to the performance factors mentioned, a commercially successful starter must be small in physical size and simple and inexpensive to replace. It is also desirable that some provision be made to open the circuit if a lamp fails to start in a reasonable time or flashes off and on at starting. Such a "No-Blink" starter is now available for 40-watt lamps (FS-4NA) and (1) eliminates the annoyance of blinking or flickering lamps, (2) protects the starter element itself, and (3) makes group replacement of fluorescent lamps practical, particularly in hard-to-get-at locations.

Occasionally the starting switch opens when the voltage is near the zero point of the cycle, and therefore the switch must repeat its operation. This is one cause of "blinks" on starting.

Fluorescent-lamp Ballasts.—A fluorescent-lamp ballast is simply a coil of wire wound on an iron core. In series with the lamp, the proper ballast will limit the current to the value for which that lamp was designed. Generally speaking, most satisfactory lamp operation is obtained when about half the available voltage (the line voltage in the case of series choke ballasts and the secondary voltage of autotransformer types) appears as the voltage drop in the arc. The other half is represented by the voltage drop at the ballast. If less than one-half the total voltage drop occurs across the lamp, the regulation is unnecessarily improved and more wattage will be lost in the ballast. When the lamp volts are more than half the total voltage, a tendency toward poor regulation results. If the ratio of lamp voltage to total voltage exceeds a certain critical value, lamp operation becomes unstable and stroboscopic effect increases.

The wattage consumed by the ballast is about 15 to 30 per cent of the lamp wattage which that ballast controls. The watts loss in the ballast depends on the lamp size, the frequency, and

the type and quality of the ballast. Sometimes the efficiency of fluorescent lamps is expressed in terms of lamp lumens per watt only, without considering the wattage consumed by the ballast. Such a practice gives an unfair advantage to fluorescent lamps—the actual over-all lumens per watt is determined by dividing the lamp lumens by the total wattage (lamp watts plus ballast watts).

For example, the rated lumens per watt efficiency of a 40-watt white fluorescent lamp is 52 lumens per watt. However, if the ballast consumes 8 watts per lamp, the over-all lumens per watt would equal the total lumen output (2100 lumens) divided by the total wattage of the lamp and ballast (40 + 8 = 48 watts). Thus, the over-all lumens per watt would be 2100/48, or 43¾ over-all LPW.

The sizes of fluorescent lamps having lamp voltages around 60 or less can be used on 110–125-volt lighting circuit with only a simple series type of ballast. If the lamp voltage is higher (such as the 40-watt size which has an approximate lamp voltage of 108), some form of transformer must be used to boost the voltage so that about the same voltage drop is allowed for the ballast. Usually this is in the form of an autotransformer, increasing the cost of the ballast and raising the wattage loss. Of course, such higher voltage lamps could be used on high-voltage circuits (such as 220 volts) without a "step-up" transformer.

Power Factor.—A choke coil such as the fluorescent ballast introduces a power factor in the electrical circuit. In addition to its normal load current, such an inductance requires a magnetizing current which lags the load current 90 deg. In the simple fluorescent circuit using a series choke, there is a differential in phase relation between voltage and current which depends on the relative amounts of load and magnetizing current. The power factor of such circuits (and of most uncorrected power-factor ballasts) is usually around 50 to 60 per cent. (The power factor of the lamp alone is about 90 per cent, less than 100 per cent because of wave distortion rather than a phase relation.) This means that only around half the line current does useful work. However, the wiring capacity must be planned for the total line current, that producing useful watts plus the wasted current.

Before the introduction of the fluorescent lamp, the lighting industry had never seriously been concerned about power factor.

Filament lamps have always had 100 per cent power factor.[1] However, about the only other things using electric power which have a good power factor are heating devices such as irons, toasters, hot pads, and electrical cooking devices. Induction motors and other alternating-current power equipments used for industrial operations, in general, have about the same power factors as do fluorescent lamps with uncorrected power-factor ballasts.

The wattless magnetizing current must be added to the useful load current in determining the economical sizes of all wires and equipments carrying that load. Therefore, branch circuits, main feeders, transformers, transmission cables, and even the wires in the generators themself must all be bigger to supply a 50 to 60 per cent power factor load than if all the current were useful (*i.e.*, a 100 per cent power-factor load). Thus, because utility companies are put to an extra expense in supplying low power factor loads, they are entitled to make an extra charge since such loads require a greater system capacity and more investment.

Power-factor Correction.—To many users, a most welcome advantage of the fluorescent lamp is the opportunity to improve existing illumination levels without the expense of rewiring. However, this advantage can be best utilized only when the power factor of the fluorescent circuit is corrected right at the lamp. This excess current can be removed and the power factor corrected to nearly unity by the use of a proper sized capacitor (condenser) connected across the line at the ballast or by the use of two-lamp ballasts whose balanced characteristics result in higher power factor.

Two-lamp Ballasts.—In the two-lamp ballast, two current-limiting devices for two lamps are contained within a single case. The "split-phase" principle is used with one of the lamps ballasted by inductive reactance only (*i.e.*, a choke coil only) and the other by inductive and capacitive reactances (choke and capacitor) in series. Figure 21 shows a cutaway of a typical two-lamp fluorescent ballast and the basic two-lamp wiring diagram.

If a circuit has a predominance of inductive reactance, the current will lag behind the voltage and the resultant power factor is called a lagging power factor. If the circuit reactance is

[1] Coiling and recoiling the filament have no practical effect on power factor.

predominantly capacitive, then the current will lead the voltage and the result will be a leading power factor. Figure 22 shows the typical representation of the voltage-current time relationships for the two conditions just mentioned.

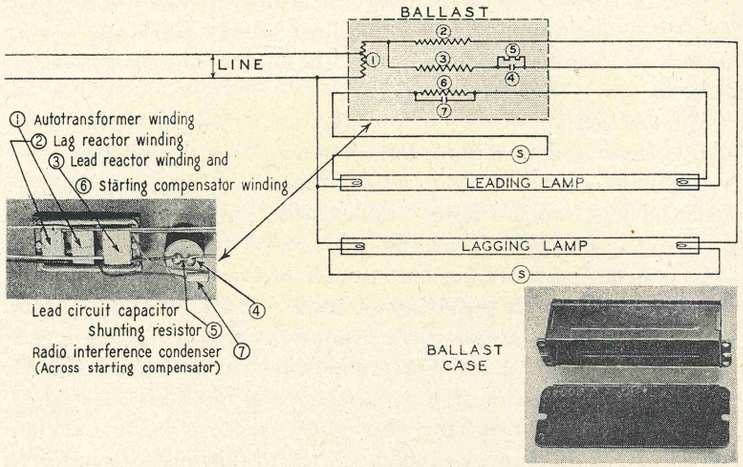


FIG. 21.—The fundamental two-lamp ballast circuit with the designation and location of the component parts of the ballast and their relation to the basic circuit.

In the two-lamp circuit, the inductively ballasted lamp has a power factor of about 60 per cent lagging. The capacitor in series with the inductive choke makes the branch of the circuit containing the other lamp predominantly capacitive, and the power factor is about 60 per cent leading. The result is an over-all power factor of 95 per cent or more, and at the same time the stroboscopic effect is reduced because of the phase displacement of the two branches of the circuit (see Chap. IV, Fig. 62). Two-lamp ballasts for 30-, 40-, and 100-watt lamps consist of an autotransformer winding and two reactor windings on a single core.

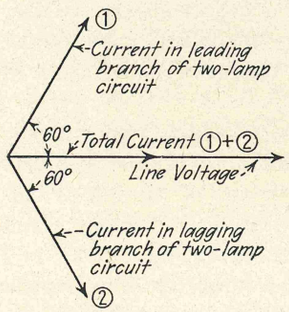


FIG. 22.—A simple vector diagram of the current in a two-lamp circuit.

The Starting Compensator.—Most present two-lamp ballasts for 15-, 20-, 30-, and 40-watt lamps require the use of a starting

compensator in series with the starter of the leading-circuit lamp. The compensator consists of a small choke coil, and its function is to alter momentarily the constant-current characteristic of the leading branch of a two-lamp circuit so that the current will rise sufficiently to permit proper cathode preheating. This helps insure satisfactory lamp life and lumen maintenance

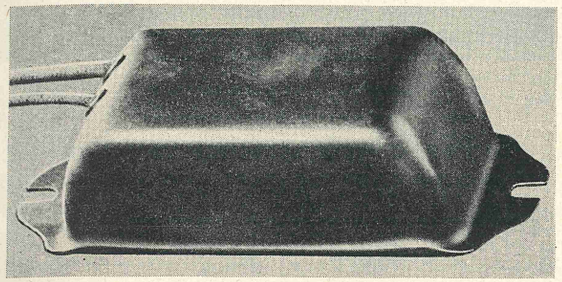


FIG. 23.—A typical separate starting compensator.

and provides more positive starting conditions at the low temperatures and voltages frequently encountered.

The starting compensator winding is located inside the case of some two-lamp ballasts and in others is connected in the circuit as a separate device (Fig. 23). Like the glow-switch starter, the starting compensator consumes power only on lamp starting.

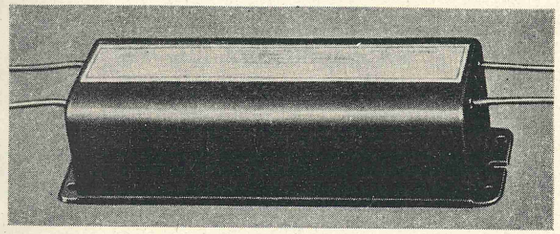


FIG. 24.—The "brick" type of two-lamp ballast.

Two-lamp ballasts for 65- and 100-watt lamps do not require starting compensators because their normal arc current is sufficient for proper cathode preheating. The separate starting compensator can be used for either 50- or 60-cycle operation.

Although the dimensions and electrical characteristics of the two-lamp ballasts made by different manufacturers vary somewhat, Table 7 indicates the two-lamp ballast line now generally

TABLE 7.—TYPICAL TWO-LAMP BALLAST CHARACTERISTICS, 60 CYCLES* With Built-in Compensator

Lamp watts	Circuit voltage	Size, inches	Weight, pounds	Approx. watts loss	Approx. power factor, per cent	Connections diagram, Fig. No.
2—15	110–125	17/32 by 2¼ by 14 ¼	3⅜	9	95–100	28
2—20	110–125	17/32 by 2¼ by 14 ¼	3⅜	9	95–100	28
2—30	110–125	2⅜ by 3⅛ by 9 ½	7	12½	95–100	29
2—30	199–216	2⅜ by 3⅛ by 9 ½	7	10	95–100	29
2—30	220–250	2⅜ by 3⅛ by 9 ½	7	10½	95–100	29
2—40	110–125	2⅜ by 3⅛ by 9 ½	7	15½	95–100	29
2—40	199–216	2⅜ by 3⅛ by 9 ½	7	11½	95–100	29
2—40	220–250	2⅜ by 3⅛ by 9 ½	7	12½	95–100	29
Small Cross Section Two-lamp Ballasts with Built-in Starting Compensator						
2—30	110–125	15/16 by 2¼ by 22 13/16	7½	18	95–100	29
2—30	199–216	15/16 by 2¼ by 22 13/16	6½	11	95–100	29
2—30	220–250	15/16 by 2¼ by 22 13/16	7½	14½	95–100	29
2—40	110–125	15/16 by 2¼ by 22 13/16	7½	24½	95–100	29
2—40	199–216	15/16 by 2¼ by 22 13/16	6½	15	95–100	29
2—40	220–250	15/16 by 2¼ by 22 13/16	7½	19½	95–100	29
Two-lamp Ballasts (Use Separate Compensator)						
2—30	110–125	2⅜ by 3⅛ by 9 ½	7	14½	95–100	30
2—30	199–216	2⅜ by 3⅛ by 9 ½	6¾	12	95–100	30
2—30	220–250	2⅜ by 3⅛ by 9 ½	6¾	12½	95–100	30
2—40	110–125	2⅜ by 3⅛ by 9 ½	7	17½	95–100	30
2—40	199–216	2⅜ by 3⅛ by 9 ½	6¾	13½	95–100	30
2—40	220–250	2⅜ by 3⅛ by 9 ½	6¾	14½	95–100	30
Two-lamp Ballasts (No Compensator Required)						
2—65	110–125	2⅜ by 3⅛ by 14 5/16	10¼	24	95–100	31
2—100	110–125	2⅜ by 3⅛ by 19 3/16	14½	32	95–100	32
2—100	199–216	2⅜ by 3⅛ by 19 3/16	14½	32	95–100	32
2—100	220–250	2⅜ by 3⅛ by 19 3/16	14½	32	95–100	32

* In most cases, similar 50-cycle ballasts are available.

available. The dimensions, weight, and wattage losses are typical of the values generally found in such equipment. Figure 24 illustrates the appearance of a typical "brick" type of two-lamp ballast. Figure 25 shows a typical small cross section two-lamp ballast for 30- or 40-watt lamps with built-in starting compensator.

High Power Factor Single-lamp Ballasts.—For single-lamp applications or for "finishing up" an installation involving an odd number of lamps, there is available a line of single-lamp high power factor ballasts for use with replaceable starters. They have a current-limiting device (choke coil) and a shunt

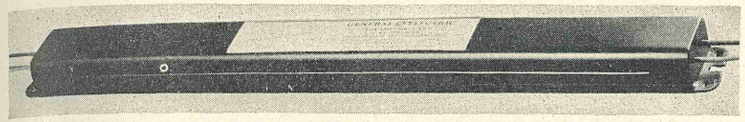


FIG. 25.—A typical small cross-sectional two-lamp ballast.

capacitor in a single container. The result is a power factor of 90 per cent lagging or higher as rated volts.

TABLE 8.—TYPICAL SINGLE-LAMP HIGH POWER FACTOR BALLAST CHARACTERISTICS, 60 CYCLES*

Lamp watts	Circuit voltage	Size, inches	Weight, pounds	Approx. watts loss	Approx. power factor	Connection diagram, Fig. No.
14	110–125	17/32 by 2¼ by 4¾	1½	3.6	85	33†
15	110–125	17/32 by 2¼ by 8¾	1½	4½		33
20	110–125	17/32 by 2¼ by 8¾	1½	4½		33
30	110–125	17/32 by 2¼ by 14¼	3½	11		33†
30	199–216	17/32 by 2¼ by 10⅝	2½	6	All 90 %	33
30	220–250	17/32 by 2¼ by 10⅝	2½	7	lagging	33
40	110–125	17/32 by 2¼ by 14¼	3½	11½	or	33†
40	199–216	17/32 by 2¼ by 10⅝	2½	10	higher	33
40	220–250	17/32 by 2¼ by 10⅝	2½	10½	at	33
65	110–125	2⅜ by 3⅛ by 14¼	9½	20	rated	34
100	110–125	2⅜ by 3⅛ by 14¼	10¼	24	volts	34
100	199–216	2⅜ by 3⅛ by 14¼	10¼	30		34
100	220–250	2⅜ by 3⅛ by 14¼	10¼	30		34

* In some cases, similar 50-cycle ballasts are available.

† External wiring same as shown in Fig. 33 but ballast is high-reactance autotransformer type.

Table 8 gives the dimensions and electrical characteristics of a typical line of high power factor single-lamp ballasts. Figure 33 gives the basic connection diagram, and Fig. 26 shows a typical ballast of this type.

Uncorrected Power Factor Single-lamp Ballasts.—Although the use of high power factor auxiliary equipment is strongly recommended, there is also available a line of uncorrected power factor single-lamp ballasts for those applications where power factor is

of little consequence, where weight and size are at a premium, or where power-factor correction is accomplished by separate capacitors or by other devices such as synchronous motors.

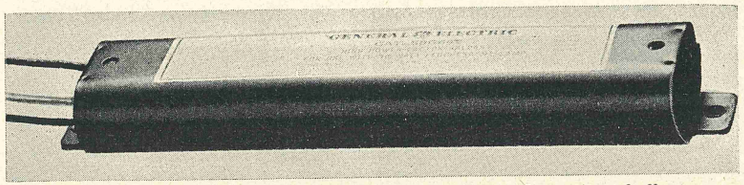


FIG. 26.—A typical single-lamp high power factor fluorescent ballast.

Table 9 gives the dimensions and electrical data of a typical line of uncorrected power factor single-lamp ballasts. Figure 36 illustrates the basic connection, and Fig. 27 shows the appearance of a typical ballast of this type.

TABLE 9.—TYPICAL UNCORRECTED POWER FACTOR BALLAST CHARACTERISTICS, 60 CYCLES*

Single-lamp Ballasts

Lamp watts	Circuit voltage	Size, inches	Weight, pounds	Approx. watts loss	Approx. power factor	Connection diagram, Fig. No.
6	110–125	1 3/16 by 1 3/4 by 4 1/4	1	2	45	35
8	110–125	1 3/16 by 1 3/4 by 4 1/4	1	2.8	45	35
14	110–125	1 7/32 by 1 3/4 by 4 1/4	3/4	3.6	44	36
15	110–125	1 7/32 by 1 3/4 by 4 1/4	3/4	4 1/2	55	36
20	110–125	1 7/32 by 1 3/4 by 4 1/4	3/4	4 1/2	55	36
30	110–125	1 7/32 by 2 1/4 by 8 3/4	2 1/4	8	55	37
30	199–216	1 7/32 by 1 3/4 by 6 1/2	1 1/2	6	60	36
30	220–250	1 7/32 by 1 3/4 by 6 1/2	1 1/2	7	60	36
40	110–125	1 7/32 by 2 1/4 by 8 3/4	2 1/4	12	60	37
40	199–216	1 7/32 by 1 3/4 by 6 1/2	1 1/2	10	60	36
40	220–250	1 7/32 by 1 3/4 by 6 1/2	1 1/2	10 1/2	60	36
65	110–125	1 7/32 by 2 1/4 by 14 1/4	3 3/4	15	45	36†
		2-multiple Ballasts				
2—14	110–125	1 7/32 by 1 3/4 by 6 1/2	1 1/2	7.2	44	38
2—15	110–125	1 7/32 by 1 3/4 by 6 1/2	1 1/2	9	55	38
2—20	110–125	1 7/32 by 1 3/4 by 6 1/2	1 1/2	9	55	38

* In most cases, similar 50-cycle ballasts are available.
† With starter connections same as in Fig. 34.

Wiring Diagrams.—Figures 28 to 38 give the wiring diagrams referred to in the last column of Tables 7, 8, and 9. A study of these diagrams helps to clarify the functioning of the component parts of the various circuits and discloses the simplicity of the basic connections.

FIG. 27.—A typical single-lamp uncorrected power factor ballast.

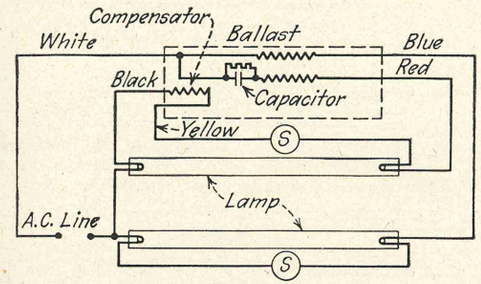


FIG. 28.—The 15- and 20-watt two-lamp circuit.

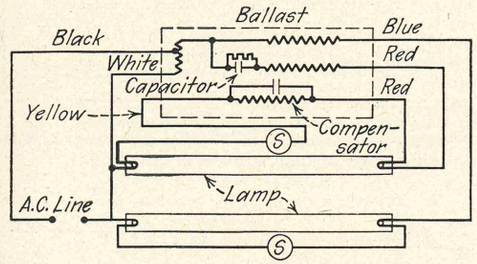


FIG. 29.—The 30- and 40-watt two-lamp circuit using a ballast with built-in starting compensator.

Circuits for the 14-watt Lamp.—As mentioned in Chap. I, it is possible to operate two 14-watt lamps in series on 110–125-volt alternating-current or direct-current circuits with a filament

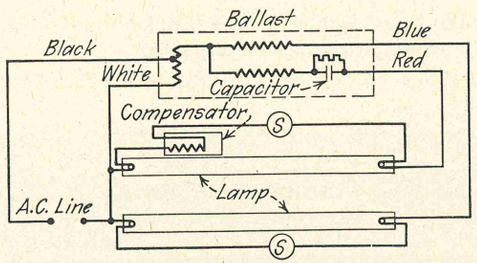


FIG. 30.—The 30- and 40-watt two-lamp circuit using separate starting compensators.

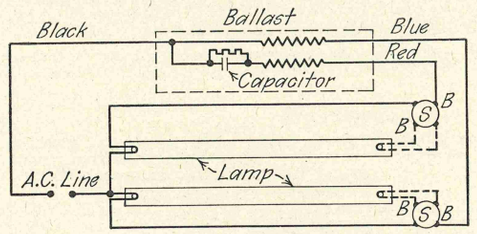


FIG. 31.—65-watt two-lamp circuits. *B* indicates the brass terminal on the starter socket. Where combination lampholder and starter-socket assemblies are used, the dotted connections are already made internally.

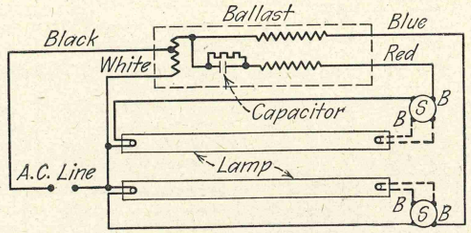


FIG. 32.—100-watt two-lamp circuits. *B* indicates the brass terminal on the starter socket. Where combination lampholder and starter-socket assemblies are used, the dotted connections are already made internally.

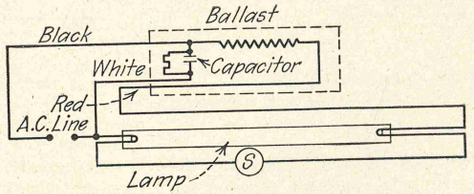


FIG. 33.—14-, 15-, and 20-watt high-power-factor single-lamp circuits. Also 30- and 40-watt 199–216 and 220–250 volts.

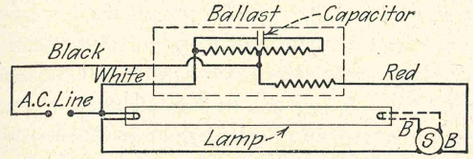


FIG. 34.—65- and 100-watt high-power-factor single-lamp circuits. *B* indicates brass terminal on the starter socket. Where combination lampholder and starter socket assemblies are used, the dotted connections are already made internally.

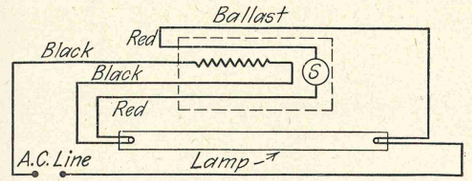


FIG. 35.—The circuit for 6- and 8-watt single-lamp uncorrected-power-factor ballasts.

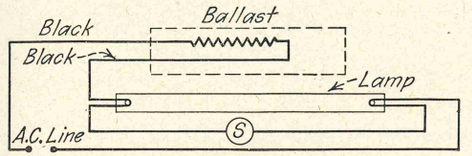


FIG. 36.—14-, 15- and 20-watt single-lamp uncorrected-power-factor circuit. Also 30- and 40-watt for 199–216 and 220–250 volts and 65-watt (for the starter connections see Fig. 34).

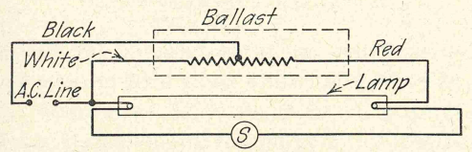


FIG. 37.—Autotransformer type of single-lamp uncorrected-power-factor ballast circuits for 30- and 40-watt lamps on 110–125 volts.

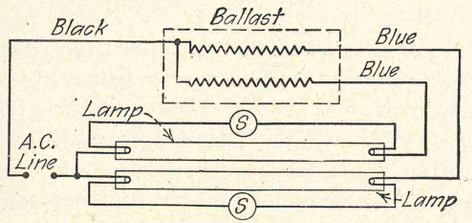


FIG. 38.—14-, 15-, and 20-watt 2-multiple circuits.

lamp as a resistance ballast. Figure 39 shows the connection diagram. The usual choke-coil type of fluorescent ballast is eliminated, the only other auxiliary equipment required being the manual starting switch and the two small radio-interference condensers. Switches are available which combine the off-and-on and the starting switch into a single unit.

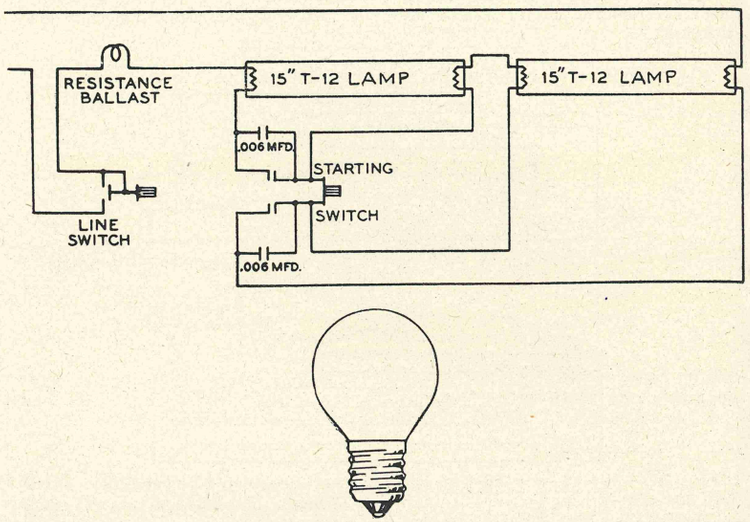


FIG. 39.—The 14-watt "two-in-series" circuit and a view of the small filament lamp used as a resistance ballast.

A small ballast lamp has been designed for this purpose. It comes in an S-11 outside-white bulb with an intermediate-screw base. The lamp is rated at 60 volts, ½ ampere. The voltage across the ballast lamp is equal to the difference between the supply voltage and the combined lamp voltage

(say 118 − 82 = 36 volts),

and so the life of the ballast lamp will be practically unlimited. The total wattage of two lamps and ballast is about 45 on alternating current and 38 on direct current. The over-all power factor on alternating-current is approximately 92 per cent with light output regulation comparable to that with a conventional single-lamp choke-coil ballast. And although the series circuit does not minimize the stroboscopic effect, it does have the

advantage of no ballast or transformer hum. As the total wattage values indicate, the 14-watt series circuit offers a fairly efficient and inexpensive method for operating fluorescent lamps on direct current, the decreased wattage loss compensating for the lower efficiency of the 14-watt lamp.

Single-lamp ballasts are also available for operating a 14-watt lamp on 110–125-volt alternating-current systems. They are listed in Tables 8 and 9 and use either an FS-2 starter or a manual

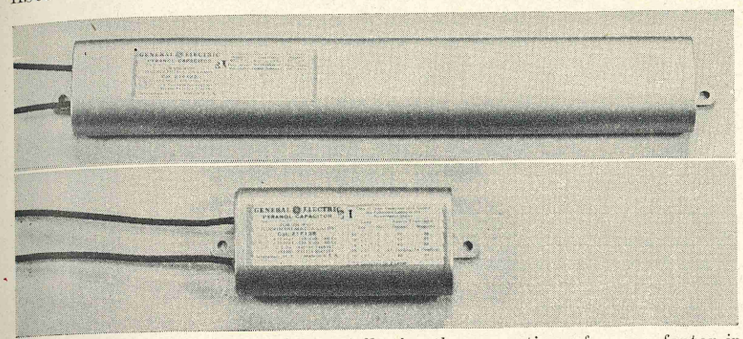


FIG. 40.—Capacitors designed especially for the correction of power factor in fluorescent-lamp circuits.

starting and operating switch. Single-lamp uncorrected power-factor ballasts for 15-watt lamps can also be employed. However, since the 14-watt lamp current is somewhat higher than that for a 15-watt lamp, the ballast saturates at the higher line voltages, and it is quite important that this combination not be used on line voltages above 125. The power factor is also less (around 45 per cent) than when the same ballast is used with a 15-watt lamp, because of the lower lamp wattage.

Capacitors for Power-factor Correction.—Wherever possible, it is recommended that the power factor of the single-lamp uncorrected power factor ballasts be improved by the application of small capacitors designed especially for this purpose (Fig. 40). When reactors and capacitors are both connected to the same circuit, one is receiving energy while the other returns it, *i.e.*, the capacitor furnishing part or all of the wasted magnetizing current of the ballast chokes and power-factor improvement results. Table 10 gives the ratings and dimensions of typical capacitors especially designed for correcting the power factor of fluorescent-lamp installations, and Table 11 indicates the number of capaci-

tors needed to correct a given number of lamps to 90 per cent power factor or better. Data on auxiliaries with built-in thermal switches have been included because many thousands of these auxiliaries are still in service.

TABLE 10.—TYPICAL RATINGS OF CAPACITORS FOR CORRECTING POWER FACTOR OF FLUORESCENT LAMPS

Capacity, microfarads	Volts	Cross section, inches	Over-all length, inches	Key*
4.75	118 236	1¼ by 2¼	5½	*A*
6.5	118	1¼ by 2¼	5½	*B*
11	118	1¼ by 2¼	6 13/16	*C*
17.5	118 236	1¼ by 2¼	14 11/16	*D*
28	118	1¼ by 2¼	14 11/16	*E*

* The key letter has no significance except to indicate the capacitor size required in Table 11.

TABLE 11.—POWER-FACTOR CORRECTION DATA

Lamp watts	Volts	Capacitors that will correct the indicated number of lamps to 90 per cent power factor or better; data for 60 cycles									
		Number of lamps, ballasts with replaceable starters					Number of lamps, thermal type auxiliaries				
		1	2	3	4	5	1	2	3	4	5
15(T-8)	118	*A*	*C*	*BB*	*D*	*CC*	*B*	*BB*	*D*	*E*	*DD*
15(T-12)	118	*B*	*C*	*D*	*CC*	*E*	*B**	*D*	*CC*	*E*	*DD*
20(T-12)	118	*A*	*C*	*D*	*CC*	*E*	*A*	*C*	*BB*	*D*	*CC*
30(T-8)	118	*C*	*D*	*E*	*DD*	*DD*	*C*	*D*	*CC*	*E*	*DD*
40(T-12)	118	*C*	*D*	*E*	*DD*	*DE*	*C*	*D*	*E*	*DD*	*CE*
30(T-8) 40(T-12)	208 236	*A*	*AA*	*AA*	*D*	*D*	*A*	*AA*	*AA*†	*D*	*D*
65(T-17)	118	*E*	*CE*	*BEE*	*EEE*	*EEEE*					

Letters indicate capacitor size from Table 10 to be used. Two letters mean those two capacitors in parallel, etc.

* Power factor 87 per cent.

† AAA for three 30-watt lamps with thermal auxiliaries on 236 volts.

Direct-current Auxiliaries.—Auxiliaries with built-in thermal switches are still available for operating certain sizes of fluorescent lamps on direct-current circuits (Fig. 41). Inductance units are also available for direct-current operation when suitable separate starting switches are employed.[1] A separate resistance of the proper value must be used in series with the choke coil of the direct-current auxiliary or inductance unit, as indicated in Fig. 42.

TABLE 12.—TOTAL CIRCUIT RESISTANCE VALUES REQUIRED FOR DIRECT-CURRENT OPERATION OF FLUORESCENT LAMPS

Lamp watts	Direct-current lamp current, amperes	Total circuit resistance, ohms*			
		110 volts†	120 volts†	220 volts†	240 volts†
6	0.141	480	550		
8	0.155	380	440		
14	0.31	212	242		
15	0.28	197	230		
20	0.31	144	176		
30	0.29	...	...	392	462
40	0.34	...	...	302	360
65	1.22	47	55		
100	1.2	...	...	113	130

* The resistance of the inductance coil and starter plus the necessary external resistor should equal the value tabulated. The value of the external resistance needed can be determined by subtracting the resistance of the inductance coil and starter. The latter should be obtained from the auxiliary or inductance unit manufacturer involved so that the value of the external resistor needed can be correctly calculated.

† If the line voltage is substantially different than the value shown, it may be desirable to use another value of external resistance. Dividing the difference in voltage by the direct-current lamp current determines the amount the calculated external resistance must be changed. For example, if a 20-watt lamp with a direct-current auxiliary having a resistance of 32 ohms, is used, the external resistance necessary on a 110-volt supply is

$$144 - 32 = 112 \text{ ohms.}$$

If the line voltage were 105 instead, the external resistance value should be

$$112 - \frac{5}{0.31} = 112 - 16 = 96 \text{ ohms.}$$

For a line voltage *higher* than shown in the table above, the value of external resistance required would be *increased* by the same method.

Although the operation of fluorescent lamps on direct current is less satisfactory than that of normal alternating-current operation, they can be used if the precautions mentioned in Chap. III are followed. Table 12 gives the total circuit resistance (resist-

[1] See p. 57.

ance of auxiliary or inductance unit and starter plus necessary external resistor) that should be used.

Lampholders and Starter Sockets.—Figure 43 shows several typical fluorescent lampholders and starter sockets. These accessory parts are generally made of molded plastic, although the details of locking the lamp vary with different manufacturers. The 90-deg. rotating lock principle is employed in most of the lampholders here illustrated.

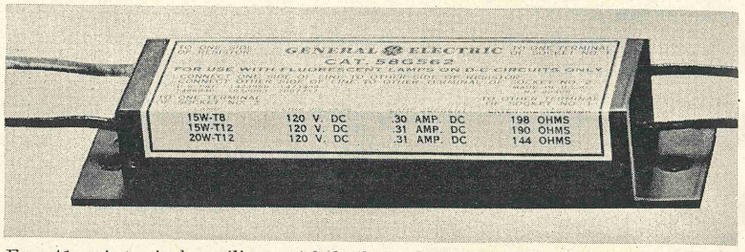


FIG. 41.—A typical auxiliary with built-in thermal switch for the operation of fluorescent lamps on direct-current circuits.

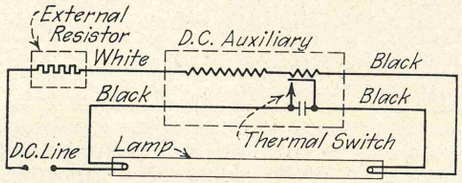


FIG. 42.—The wiring diagram for the direct-current auxiliary.

The starter socket can be mounted with one lampholder by the manufacturer (two assemblies of this type are shown in Fig. 43) or obtained as a separate unit for flush or surface mounting. Figure 44 illustrates the use of combination lampholder-starter socket assemblies, starters being readily accessible (Fig. 45) simply by removing the lamp.

The mounting dimensions for typical lampholders will be found in Chap. IV.

High-voltage Cold-cathode Starting.—Fluorescent-lamp developmental work has included both the operating of strings of lamps on several thousand volts and single- or two-lamp operation from smaller transformers where starting is accomplished by higher voltage and without cathode preheating. Although such systems are not dependent on cathode preheating and starter troubles are eliminated, it is known that "cold-cathode" punish-

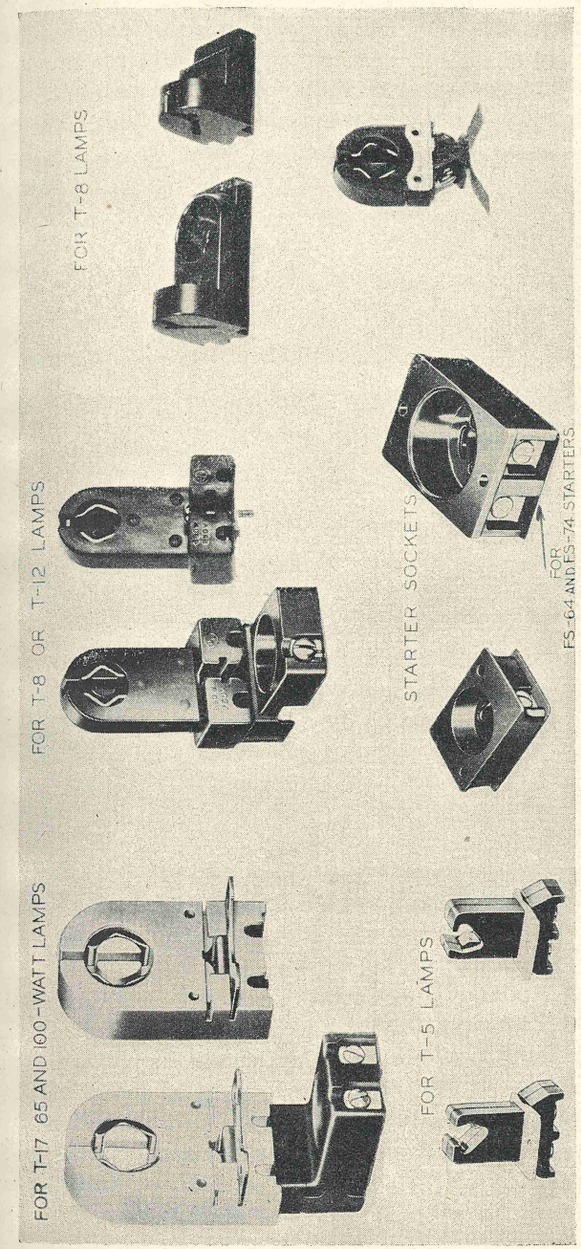


FIG. 43.—Typical fluorescent lampholders and starter sockets.

ment is more severe on starting than with properly preheated cathodes.

Although further study of these above-mentioned cold cathode starting schemes is being actively pursued, it appears that operation from standard low-voltage preheated-cathode auxiliary equipments is superior to that from other equipment now available as regards over-all efficiency of light production, lamp service, safety, and general satisfaction. New developments may, of course alter the situation.

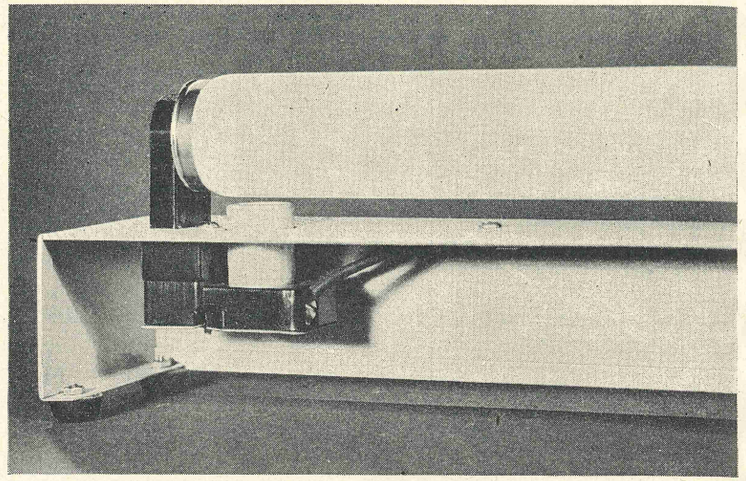


FIG. 44.—A view of the lampholder and starter socket combination in use showing how the end of the starter projects through the reflector for easy replacement.

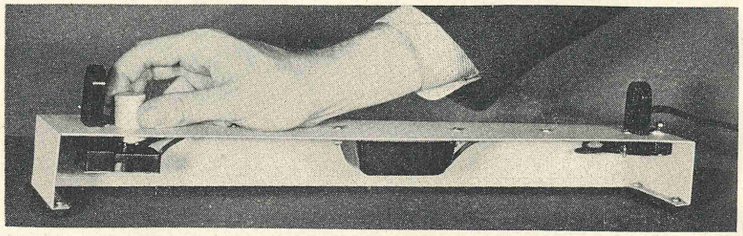


FIG. 45.—The starter is inserted and locked in contact by a slight turn in a clockwise direction. The starter is removed by reversing the procedure.

Auxiliary Equipment for Type RF Lamps.—The type RF lamp is intended for use in industrial lighting, and RF units consist of reflector and auxiliary mounted together (Fig. 46).

The auxiliary design has been changed recently, and the new circuit is more simple and contains no moving parts. Also, the RF lamp has been improved of late and now has a quick-heating cathode which results in almost instantaneous starting. Lamps

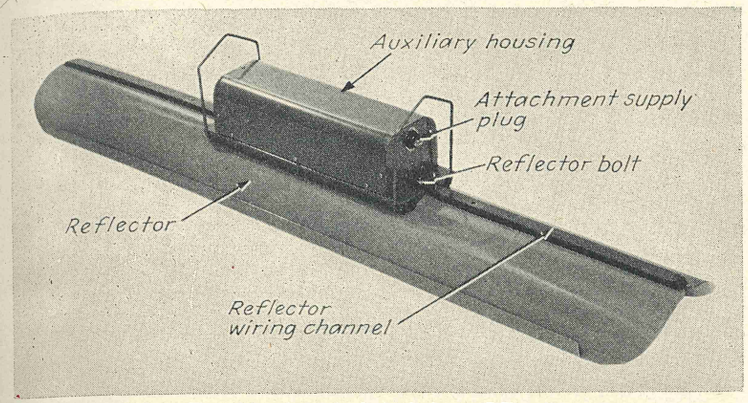


FIG. 46.—A typical single-lamp RF unit.

of the latest design can be used with either the former type of auxiliary or with the new simplified type.

The circuit for the new simplified RF auxiliary is shown in Fig. 47 and can be compared with the older circuit (Fig. 48). The complete RF unit now consists of the tube B, an auto-

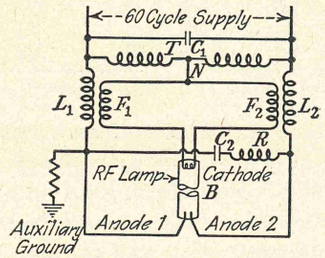


FIG. 47.—The wiring diagram of the new simplified single-lamp RF circuit.

transformer T, two ballast coils L_1 and L_2, cathode heater windings F_1 and F_2, a starting coil R, and two capacitors C_1 and C_2. The autotransformer is center tapped and provides two anode connections and a cathode connection at the neutral point. The ballast coils limit the arc current as in the case of standard fluorescent lamps, and the heater windings are simply low-voltage

secondaries which serve to keep the cathodes at operating temperatures. The cathode is continuously heated from these low-voltage windings, even while the lamp is in operation.

The starting coils and capacitors are so chosen that the resonant frequency of the combination is sharply tuned to 60 cycles, the frequency of the supply current. Thus, a greatly amplified voltage of the order of 500 to 550 volts is produced across the

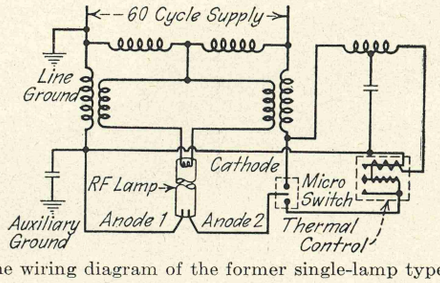


FIG. 48.—The wiring diagram of the former single-lamp type RF circuit.

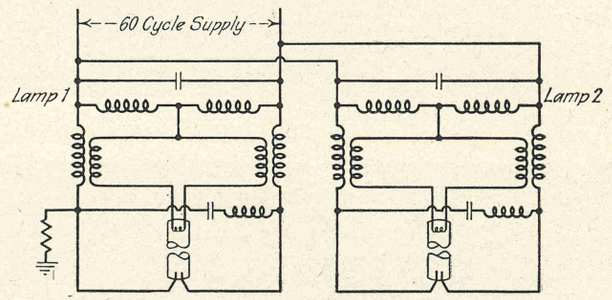


FIG. 49.—The wiring diagram of the new simplified two-lamp RF circuit.

lamp anodes for starting. This voltage is not sufficient to start the mercury arc, but a small quantity of argon is present in the bulb and this breaks down, allowing an appreciable current to flow between the anodes. This current is sufficient to cause ionization of the mercury vapor and to cause the lamp to start. Once the lamp has been started, it functions as a full-wave mercury-vapor rectifier. That is, current flows only from the cathode to one anode or the other at the opposite end. Thus the current flow is unidirectional throughout the tube. The power factor is 90 per cent or better.

Figure 49 shows the new simplified auxiliary circuit diagram for two-lamp RF units.

CHAPTER III

OPERATING CHARACTERISTICS

Influence of Supply Voltage.—Ballasts for 110–125-volt circuits have their design center at 118-volts, 199–216-volt ballasts at 208 volts, and 220–250-volt ballasts at 236 volts.

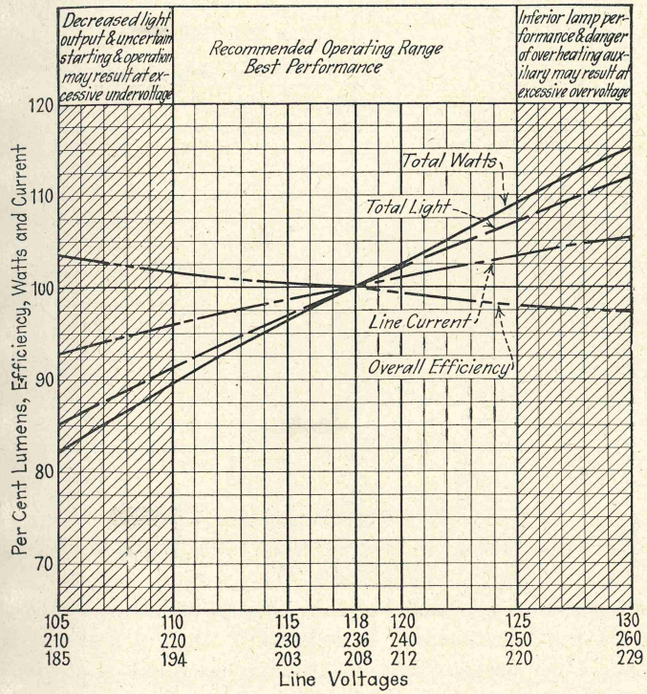


FIG. 50.—Characteristic curves of a typical two-lamp fluorescent ballast.

The characteristic curves in Fig. 50 show the effect of various line voltages on the total input wattage, the total lumen output, the line current, and the over-all efficiency for typical two-lamp fluorescent ballasts. These curves are the average for both the

leading and the lagging power factor lamps; similar characteristics for the lagging lamp are given in Fig. 51 and for the leading lamp in Fig. 52.

In general, these characteristics depend largely on the quality of the ballast choke. It will be seen from Fig. 50 that the total lumen output of a typical two-lamp ballast circuit varies a little

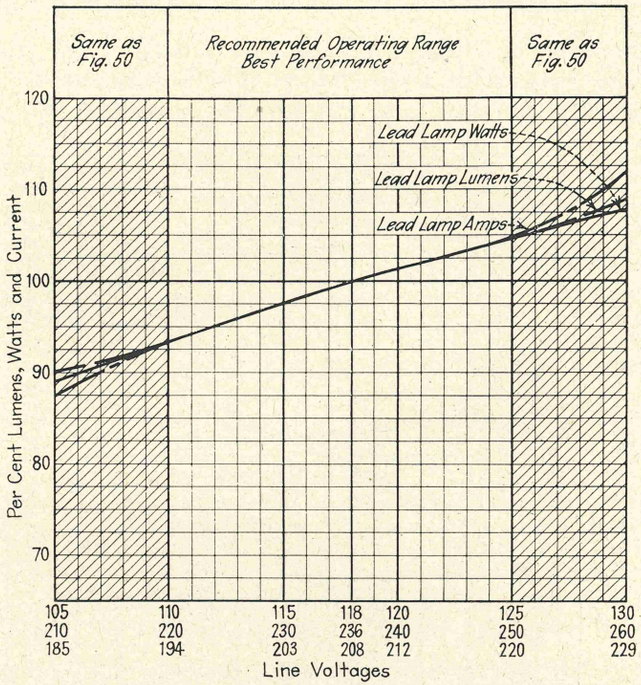


Fig. 51.—The lead-lamp characteristic curves of the typical two-lamp ballast referred to in Fig. 50.

over 1 per cent for each per cent change in line voltage. This light output "regulation" is superior to that of filament lamps where a 1 per cent voltage variation causes about a 3½ per cent change in lumen output.

It is interesting to note that the lamp voltage goes down as the line voltage goes up, and although the lumen output increases, the over-all efficiency actually decreases. This condition is due to the fact that the increased line voltage causes the ballast to pass more current to the lamp, which lowers the resistance of

the discharge path and results in a lower voltage drop across the lamp itself. The input watts to the lamp itself are slightly increased, and therefore the lumens increase over a certain range. In this condition, however, the higher current density produces the short ultraviolet radiation less efficiently. Consequently, the luminous efficiency of the lamp decreases.

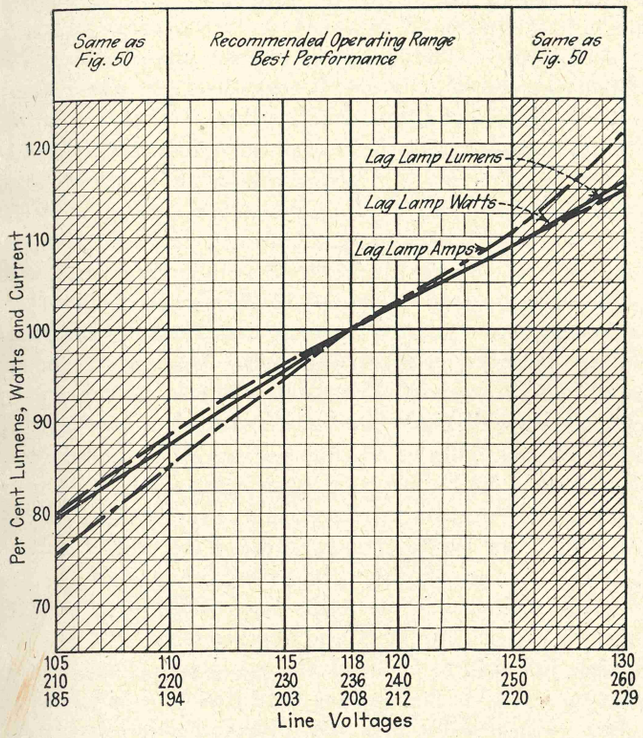


Fig. 52.—The lag-lamp characteristic curves of the typical two-lamp ballast referred to in Fig. 50.

An examination of Figs. 51 and 52 will show that the variation in light output from the lagging lamp is greater than for the leading lamp. This effect results because the leading branch is essentially a constant-current circuit. Thus when the line voltage is at some other value than the design center for the ballast, there may be a slight difference in brightness between the leading and the lagging lamp of a two-lamp unit. For a

well-designed two-lamp ballast, this brightness difference will be difficult to detect with the eye.

Recommended Voltage Ranges.—Fluorescent lamps are designed to give their best all-around performance when operated on line voltages within the range for which the ballast was designed. This range is clearly indicated on the ballast name plate. Decreased light output and uncertain starting and operation may result at excessive undervoltages, and inferior lamp performance and danger of overheating the ballast may accompany excessive overvoltage operation. In either case, the lamp life is likely to be shortened.

Although satisfactory performance and operation of fluorescent lamps can be expected through a range of line voltages (such as 110–125 volts for normal-voltage ballasts), care must be taken to operate within the recommended range. As will be discussed in Chap. V, low voltage, for example, is much more important in fluorescent-lamp operation than with filament lamps.

Voltage Surges.—Because there are many factors that influence the voltage condition at which fluorescent lamps will "black-out" completely, it is impractical to state definite cutout points for the various lamp sizes. Generally speaking, however, a drop of 25 per cent or more in the line voltage will cause fluorescent lamps to "drop out." Where glow-switch starters are employed, it is conceivable that on prolonged and severe voltage drops the lamp voltage may go up enough to cause the starter to reglow. In such a case, the arc would be extinguished, and the starter cycle would be repeated until the line voltage was sufficiently restored for the lamp to start and operate normally.

Starting Reliability.—One of the most important factors in starting reliability is line voltage, and it should be remembered that line voltages lower than those recommended may result in unsatisfactory starting. Other starting reliability factors include the type of starter, type of ballast, the age of the lamp, the age of the starter, probability (because the voltage wave may be close to zero when the switch opens). Because of all these factors, it is impractical to quote definite minimum line voltages for satisfactory starting reliability.

Outdoor Weathering of Ballasts.—Most fluorescent-lamp ballasts are designed for indoor installation and should not be used when directly exposed to weather or when excessive moisture

conditions prevail. Where it is necessary to locate ballasts outdoors, it is recommended that they be protected in some way from the weather. If they are completely enclosed, however, suitable ventilation should be provided so that the temperature around the ballasts does not exceed 120°F. during normal operation.

Frequency.—Both 60- and 50-cycle distribution systems are used in this country, and ballasts for either frequency are available. For best results, they should be used on the frequencies for which they were designed. However, satisfactory performance can be expected in the range of 57½ to 62½ cycles for nominal 60-cycle ballasts and in the range of 47½ to 52½ for nominal 50-cycle ballasts.

Fluorescent lamps themselves will operate on 25-cycle circuits, but at this frequency the flicker is unsatisfactory unless special precautions are taken in installation and circuit arrangement. When such an installation must be made, it is suggested that (1) white lamps be used in preference to daylight, (2) that lamps either be covered with black paint for about 2½ in. on each end or the ends otherwise shielded from view, and (3) that alternate operation from each phase of a three-phase system be employed wherever possible.

TABLE 13.—STROBOSCOPIC EFFECT

Lamp	Deviation from Mean Light Output,* Per Cent
Daylight	55
White	35
Daylight (two-lamp ballast)	25
White (two-lamp ballast)	16
Blue	90
Gold	25
Green	20
Pink	20
Red	10
40-watt filament lamp	13
100-watt filament lamp	5

* On 60-cycle circuits.

Stroboscopic Effect.—Every lamp, when burned in the usual manner on alternating current, has a nonuniform light output caused by the cyclic variations in current. This effect is, of

course, increased at lower frequencies. In electric-discharge lamps where practically no energy is stored (as it is in the hot tungsten of a filament lamp), the light drops almost to zero along with the current between each half cycle. However, all the fluorescent powders but the one producing the blue color have a persistence of glow, or phosphorescence, which helps to reduce flicker in various colors of fluorescent lamps when operated from a 60-cycle circuit. Table 13 indicates the flicker of various

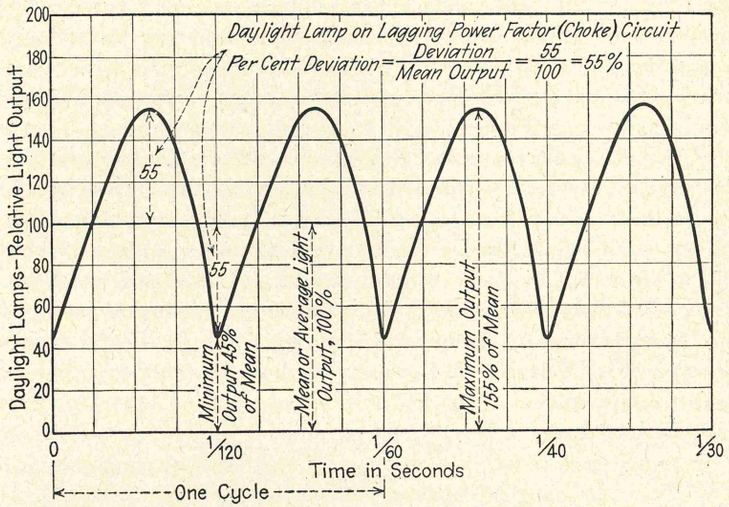


FIG. 53.—The variation of light output with time (stroboscopic effect) for a daylight fluorescent lamp.

lamp colors in terms of the approximate percentage deviation from the mean, or average, light output (Fig. 53). Operation on two or more phases or with two-lamp ballasts brings the lamps out of phase, and the fluctuation in light output is further reduced and becomes comparable to the variation in low-wattage filament lamps (Figs. 62 and 63).

Although stroboscopic effect, or flicker, is not known to be harmful to the eyes, it may produce disconcerting effects when viewing rotating machinery and the like.

Direct-current Operation.—Whereas fluorescent lamps are designed for alternating-current operation, they may be used on direct-current circuits if an approved direct-current auxiliary or inductance unit and a series resistance (Table 12) of the correct

value are employed. The resistor is necessary, for the ballast choke has insufficient current-limiting effect on direct current. The auxiliary simply provides for cathode preheating and supplies the inductive kick needed to start the lamp. The series resistance consumes about as much wattage as the lamp itself, and thus the over-all efficiency of light production on direct current is only about one-half that of normal alternating-current operation.[1] Direct-current operation usually results in decreased useful lamp life and inferior lumen maintenance and starting reliability. On the other hand, color quality and total light output of the lamp compare favorably with alternating-current operation, and the stroboscopic effect is, of course, completely eliminated. Installations of 30- and 40-watt fluorescent lamps on 230-volt direct-current circuits are being equipped with a reversing switch to overcome the "dark-end" effect (very much less bright at one end) resulting when long lamps are operated on direct current. This effect is due to mercury pumping—*i.e.*, the unidirectional current flow tends to pull the mercury vapor away from the positive end of the lamp to the internally negative end. Reversing the connections to the circuit once a day practically eliminates this effect. Thirty- and 40-watt lamps cannot be operated from a direct-current supply of less than about 200 volts.

Because of the high wattage loss in the series resistance, care must be taken to avoid excessive temperatures. Resistors especially designed for this service can be obtained from several resistance manufacturers.

Present glow-switch starters are not recommended for operation on direct current. When a direct-current inductance unit is used instead of the direct-current thermal-switch auxiliary for lamp sizes up to and including 40 watts, a manual starting button or thermal-switch type of starter must be employed, with a 0.006- to 0.05-mf condenser connected across the contacts. The FS-44 thermal-switch starter can be used with 40-watt lamps on direct current, and the FS-74 starter is satisfactory for the 65- and 100-watt lamps.[2]

[1] The 14-watt two-in-series circuit is an exception as mentioned in Chap. II.

[2] It would be difficult, however, to justify using the 100-watt lamp on direct current because of the high wattage loss.

The Effect of the Surrounding Temperature.—When a fluorescent lamp is operated at the usual surrounding, or "ambient," temperature, much of the heat generated by the arc must be radiated. But when the lamp is operated in very low ambient temperatures or at low brightness levels, the heat from the arc may not be sufficient to produce optimum bulb-wall temperatures (see Fig. 4), and under those conditions the lamp efficiency and

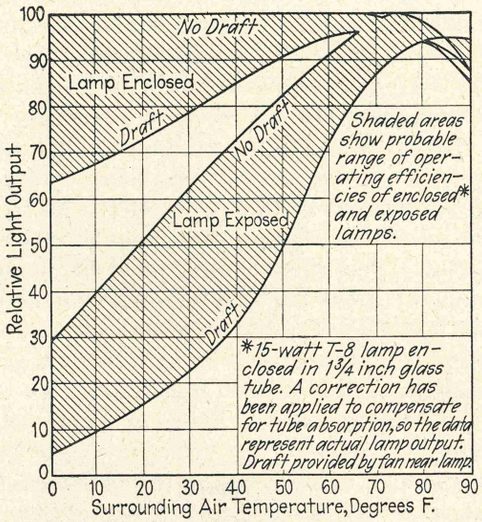


FIG. 54.—The effect on light output of the surrounding air temperature. The curves shown here are for a 15-watt T-8 lamp with and without a 1¾-inch glass tube. The data are similar for other most common sizes of lamps.

light output are reduced. Lamps operate at their highest efficiency at normal room temperatures of 70 to 80°F., where the temperature of the glass tube itself has a value of 100 to 120°F. Besides the loss due to less favorable bulb temperature as mentioned above, the mercury vapor condenses out at lower ambient temperatures and less of the ultraviolet radiation is produced to activate the fluorescent chemicals. If the ambient temperature is too high, the mercury-vapor pressure is increased and some of the ultraviolet radiation is shifted from 2537 Å. to longer wavelengths which the phosphors convert less efficiently into visible light. Too, there is increased reabsorption of the 2537 radiation by the mercury vapor. Under operating conditions, of course, the bulb temperature will be affected not only by the temperature of the surrounding air but also by the air movement and by any enclosures used around the lamp.

Figure 54 shows the effect on the relative light output of the surrounding air temperature with ranges indicated for conditions of exposed and enclosed lamps. The data are for a 15-watt 18-in. T-8 lamp with and without a 1¾-in. glass tube, but they are, in general, applicable to the other fluorescent lamp sizes as well.

The mutual heating of lamps in a fluorescent luminaire may raise the ambient temperature and reduce the total light output unless proper consideration has been given to dissipation of the heat. A more complete discussion of this problem will be found in Chap. VI.

Fluorescent lamps have been used satisfactorily as exposed porch lights throughout winter months, and they have been commonly applied in enclosed transom areas of store fronts. The light output in the colder months falls off somewhat, but no operating difficulties should be experienced. In fact, adverse effects of low surrounding air temperature can be offset to a great extent by enclosing the lamp.

Low-temperature Operation.—Fluorescent lamps start best and give their most satisfactory light output at surrounding air temperatures of 65 to 90°F. As shown by Fig. 54, the light output of exposed lamps falls off somewhat with temperatures above 95°F., but at temperatures below 65°F. the decrease may amount to 1 per cent per degree Fahrenheit or even more under draft conditions.

In general, lamps of lower operating voltage start easiest at low temperatures. At very low temperatures, the lead lamp of a two-lamp ballast circuit starts more easily because the lamp voltage is a little higher in that branch of the circuit. At ordinary temperatures, lamps start easiest on lag circuits. The proximity of metal in the form of wireways, channels, conduits, etc., also helps starting.

From the standpoint of starting and operation, no special restrictions need be applied where surrounding temperatures are not below 50°F. and provided the circuit voltage is within the recommended range. Lamp performance below 50°F. depends on the type of starter switch used, the circuit voltage, and the age

of the lamp. In most cases, satisfactory starting and performance should be obtained at temperatures considerably below 50°F. by complying with the following:[1]

1. Keep the line voltage up, preferably in the *upper half* of the ballast rating.

2. Conserve the lamp heat by enclosure or some other suitable means. This improves both the lamp operation and the light output.

3. Use starters that consistently provide high induced starting voltages (sharp breaks) and longer cathode heating periods than are required for starting at normal temperature (such as the FS-44 thermal-switch starter for 40-watt lamps). From the standpoint of ease of starting, the magnetic switch used in the earlier type of magnetic auxiliaries rates first among the automatic starting devices with the thermal switch second. (A manual starting switch shunted by a 0.05-mf. condenser will also help provide reliable low-temperature starting and is often recommended for refrigerated meat case operation as mentioned in Chap. IX.)

Although the difference may not be noticeable under most conditions, the glow switch is rated third because, even though the gas glows properly at low temperatures, part of the inductive kick is by-passed through the conducting gas and therefore less energy is available for starting the lamp. Both thermal and magnetic switches conserve this kick and are, therefore, better for low-temperature operation than the glow-switch starter.

At temperatures below 32°F., starting trouble is likely to be experienced.[2] Unsteady lamp operation may also result, and reductions in lamp life and light output are probable, depending on the degree to which the precautions above mentioned are observed. Of course, conditions may be improved by the use of secondary sources of heat.

As mentioned in Chap. I, the 65- and 100-watt T-17 fluorescent lamps (as well as the RF lamp) have somewhat higher loading factors, *i.e.*, watts per square inch of lighted surface, and are

[1] Where 40-watt lamps are involved, satisfactory starting down to 0°F. can be secured simply by using the low-temperature 40-watt lamp now available (see Table 3).

[2] Except as previously mentioned.

better able to maintain a favorable bulb-wall temperature at low ambient temperatures. On the other hand, the light output of these lamps falls off considerably at high bulb temperatures (high ambients).

Dimming and Flashing.—Fluorescent lamps with the present types of auxiliary equipments are not adapted to either flashing or dimming applications. Especially designed equipment is necessary for satisfactory performance, but auxiliaries for this service are not at the present commercially available.

Since frequent starting of lamps may take more life out of the electrodes than long hours of burning (because momentarily at starting there is a higher than normal voltage drop at the electrodes which causes the active material on the cathode to sputter or evaporate off), flashing of fluorescent lamps is not recommended because of the harmful effect on lamp life. Too, the exact instant of starting with either the glow- or thermal-type switch or starter cannot be predicted with any degree of accuracy. However, a system of flashing filament lamps incorporated with a fluorescent-lamp sign can be used to obtain a very pleasant flashing effect. This system is described in Chap. IX.

Transformer Hum.—Characteristic "transformer hum" is inherent in lamp-ballast equipment, although the noise may come and go and vary considerably with individual ballasts. Noise or hum originates from the magnetic action in the ballast core-and-coil element and is aggravated when the vibrations are transmitted to the supporting frame or metallic panel. By mounting ballasts on soft rubber or placing some similar non-rigid material between the ballast and metallic mounting, the disconcerting ballast hum can be reduced to a negligible level.

Channels, metallic mounting frames, reflectors, etc., associated with the ballast should have sufficient mechanical strength and be so bonded together that hum will be reduced to a minimum. Fixtures made of thin materials tend to vibrate of their own accord.

Where surrounding noise levels are extremely low, as in homes and churches, it is recommended that wherever possible the ballast or auxiliary equipment be mounted away from the light source in a location where noise will not be a problem. Successful fluorescent installations have already been made where ballasts were located in attics or basements of homes and

in soundproof rooms in churches, theaters, etc. Lack of sufficient ventilation and overvoltage operation are also known to increase transformer hum. In the former regard, care should be taken that materials used to insulate the noise do not seriously interfere with the normal radiation and conduction of heat from the ballasts.

CHAPTER IV

INSTALLATION HINTS

Safeguards to Satisfactory Service.—Every successful merchant knows that the customer must be satisfied with the performance that a product gives "in service" if he is to remain a satisfied and loyal buyer. So it is with fluorescent lighting. Once the novelty of a new fluorescent installation wears off, the owner may appraise its performance and servicing requirements by his well-founded notions of the simple operation of filament lamps. Therefore, the installer must be exceedingly alert in planning fluorescent-lighting installations for the maximum of both present and future satisfaction of the customer.

There are a number of safeguards to satisfactory service, which, if carefully followed, will prove beneficial to both the owner of the installation and the installing agent. Some of the most important are the following:

1. Tailor the lighting to the seeing task, following all the well-known principles of illumination design as regard footcandle levels, lighting quality, and color quality.
2. Use only approved equipment. This includes every line of the fluorescent chain—fixtures, ballasts, starters, and wiring methods and materials.
3. Make sure that all equipments are complete, properly assembled, and correctly connected.
4. Explain the principles of maintenance to the customer (see Chap. V).

The following suggestions will be helpful in actually completing the installation and will indicate some of the precautions that should be taken to insure satisfactory future performance.

Burning Position.—Standard fluorescent lamps can be operated in any position, but present RF fluorescent reflectors must be hung so the anode (two-prong) end is at least 3 in. lower than the cathode (three-prong) end (Fig. 55). This position is accomplished by making the suspension member at the anode end of the

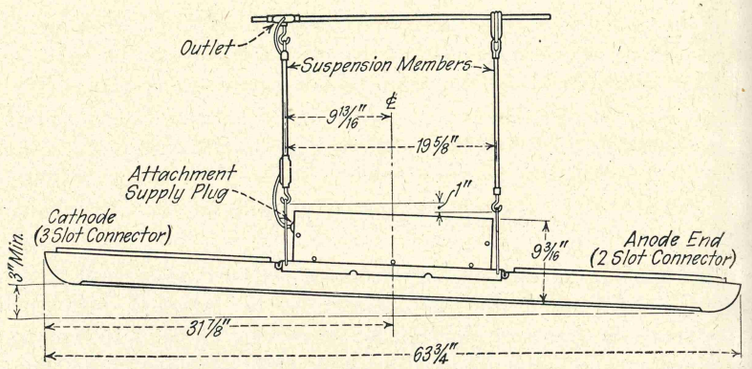


FIG. 55.—Present type RF fixtures should be hung so that the anode (two-prong) end is 3 in. lower than the cathode end, as shown. This is accomplished by making the suspension member on the anode end of the auxiliary 1 in. longer than on the cathode end.

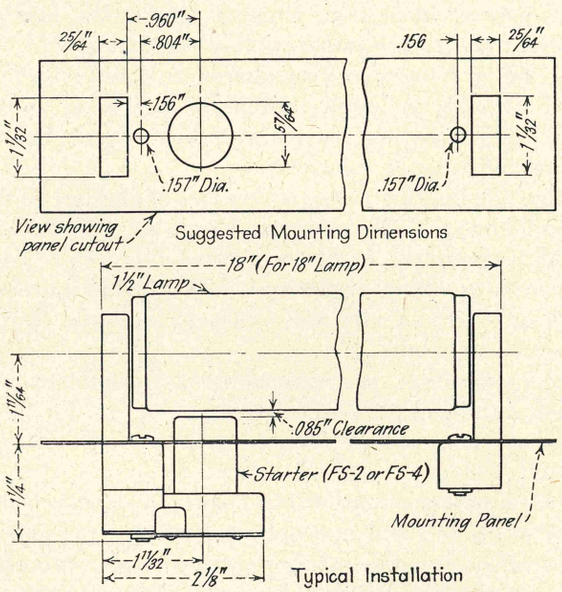


FIG. 56.—Lampholder mounting dimension for medium bipin-base fluorescent lampholders.

RF auxiliary 1 in. longer than that on the anode end. The anode end of the reflector may be more than 3 in. below the cathode end—diagonal or vertical operation is permissible if the anode end of the lamp is down.

Lampholder Mounting Positions.—Although the fluorescent fixture manufacturer is most concerned about the proper spacing of lampholders, Table 14 is included because there are many

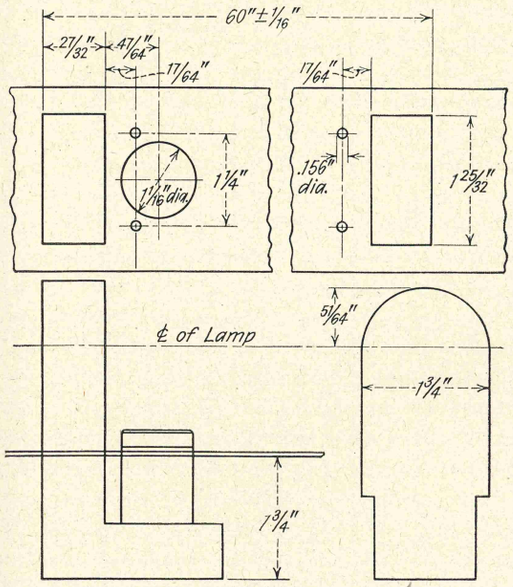


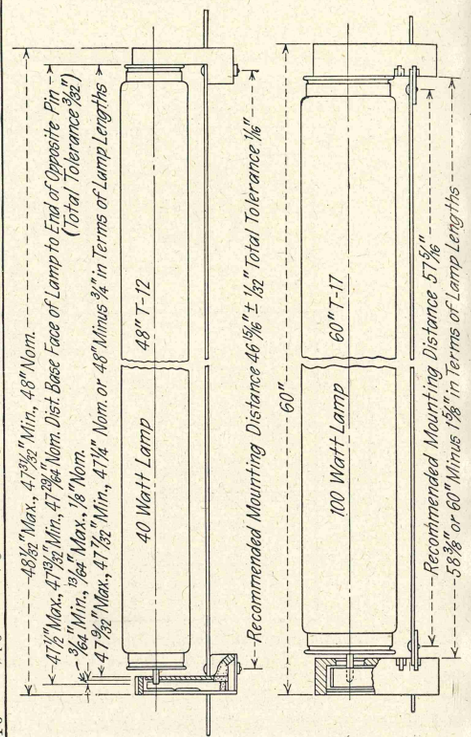
FIG. 57.—Lampholder mounting dimension for mogul fluorescent lampholders (65- or 100-watt T-17 lamps).

instances where such information is most helpful. Also, the data enable the checking of lampholder spacing distances in luminaires being installed to make sure that lamps will be securely supported and will have proper electrical contacts. Figures 56 and 57 give mounting dimensions for typical lampholders.

It will be noted from Table 14 that the nominal over-all lamp length (such as 18, 24, 48, or 60 in.) includes one lamp and two typical lampholders. Thus continuous rows of 30-watt lamps, for example, would be on 36-in. centers. For this reason, the

TABLE 14.—FLUORESCENT LAMPHOLDER SPACING REQUIREMENTS

Lamp watts	6(T-5)	8(T-5)	14(T-12)	15(T-8)	15(T-12)	20(T-12)	30(T-8)	40(T-12)	65(T-17)	100(T-17)
Spacing of lampholders, back-to-back dimension (nominal lamp length), inches	9	12	15	18	18	24	36	48	36	60
Tolerance in lampholder spacing, inches	1/32	1/32	1/32	1/32	1/32	1/32	1/32	1/32	1/16	1/16
Thickness of typical lampholder, inches	5/16	5/16	3/8	3/8	3/8	3/8	3/8	3/8	13/16	13/16



Typical illustration of lampholder spacing dimensions given in Table 14.

nominal length is of more importance than the maximum over-all length (pin tips to pin tips) of fluorescent lamps.

Mounting Ballasts.—As described in Chap. III, the transformer hum which results from the magnetic action in the ballast is aggravated when the vibrations are transmitted to the supporting frame or metallic wiring channel. Recent improvements in ballast construction have helped minimize this hum, but it is now considered good practice to mount ballasts with grommets or washers of some vibration-insulating material such as rubber. If rubber washers are used, they should be placed both under the ballast mounting feet and between the screw head and the mounting feet. It is wise to insulate the threads of the screw also. Care should be taken, however, that the mounting materials do not reduce heat radiation and conduction to the extent that the ballast will overheat.

It is also possible for the continuous though minute vibration of ballasts gradually to loosen the screws by which they are mounted. To insure tight mechanical connections, the use of lock washers or lock nuts is recommended.

Ventilation.—Ballasts and lamps, like all other types of electrical equipment, generate heat during their normal operation which must be dissipated by radiation and by conduction and convection to the surrounding fixture parts. In order to prevent damage to the ballasts, it is important that the ballast enclosure in the fixture or wireway be suitably ventilated and lamps and ballasts located far enough apart so they will not overheat each other. Ambient temperatures around the ballasts should not exceed 120°F. during normal operation.

If it is found that the ballast housing temperature is too hot, one or more of the following steps should be taken:

1. Ventilate the housing if possible (make holes at the bottom and the top of the housing if possible to use the "chimney effect").
2. Remove sound-insulating washers to increase the radiating surface area.
3. If the washers are required to keep noise level down, bolt a larger plate to the case of the ballast and then mount that plate to the housing with sound-insulating washers.
4. Paint the inside of the compartment black or some other dark color.

5. Try to guard against operation

   a. At excessive voltages.
   b. On the wrong frequency.
   c. With the wrong-sized lamp.

Vibration.—The electrodes of fluorescent lamps are quite rigidly constructed and are able to withstand a good bit of vibration without damage. However, any lamp will be harmed if subjected to extreme vibration, and the fluorescent lamp is no different in this respect.

It should be remembered that severe vibration can impair the electrical connections at the lampholder, and may be as important as damage to the physical parts of the lamp themselves. This could, of course, have serious results as regards lamp performance and lamp life. For installations where vibration is more severe than usually encountered in ordinary lighting work, some precaution should be taken to insure adequate and continuous electrical contact at the lampholders.

Distance from Ballasts and Starters to Lamps.—The two-terminal glow-switch starter in common use today is frequently located near one lampholder, the starter socket in many cases being actually combined with one of the lampholders. This arrangement is perhaps the most economical from the standpoint of connecting wire required. However, there are cases where it is more convenient to use separate starter sockets, usually so mounted that the starter can be removed without taking out the lamp. These separate starter sockets can be located at any reasonable distance from the lamp provided the voltage drop in the wires is not excessive. In fact, distances up to 50 ft. may be employed without concern.

Likewise, ballasts can be located at any convenient distance from the lamp provided the voltage drop is within reason. These distances may vary from just a few feet for showcases to 50 ft., for example, where ballasts controlling outdoor fluorescent-lamp signs are located indoors.

Of course, where four-terminal thermal-switch starters are involved, more wiring is required than for glow-switch starters unless the lampholder and starter socket combination assemblies are employed (Fig. 58). Too, considerably more copper would be necessary to connect four-terminal starters mounted at a

distance from the lamp. If two-lamp ballasts must be located at some distance from the lamp, a saving in wiring can be effected by using the separate starting compensator wherever space permits. An extra pair of leads will be required if two-lamp ballasts with built-in starting compensators are used in such instances.

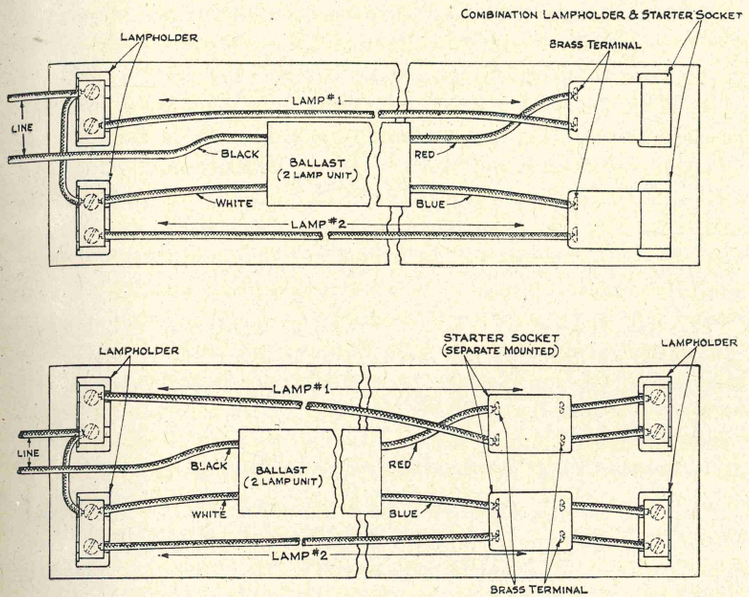


FIG. 58.—Detailed connection diagrams for four-terminal thermal switch starters mounted separately or with one lampholder.

Calculating Line Currents in Branch Circuits.—Among the rating information found on a fluorescent-lamp ballast label is the line current in amperes which that ballast will draw in supplying power to the one or two lamps it controls. This value of line current determines the number of lamps that may be connected to a circuit of definite current ratings. For example, 34 40-watt lamps controlled by high-power factor two-lamp ballasts could be used on a 15-ampere circuit. Table 15 shows the maximum number of various sized lamps which could theoretically be placed on a 15-ampere branch circuit when various types of ballast are used. The theoretical capacity of

any other circuit can be obtained by simply multiplying the values in Table 15 by the current-capacity ratio.

TABLE 15.—MAXIMUM NUMBER OF LAMPS ON 15-AMPERE BRANCH CIRCUIT*

Lamp, watts	High power factor two-lamp ballasts			High power factor single-lamp ballasts			Uncorrected power factor single-lamp ballasts		
	110–125 volts	199–216 volts	220–250 volts	110–125 volts	199–216 volts	220–250 volts	110–125 volts	199–216 volts	220–250 volts
15	84	..	..	79	..	..	50		
20	66	..	..	65	..	..	42		
30	42	74	84	41	65	75	23	44	44
40	34	60	68	30	51	57	17	36	36
65	20	..	..	16	..	..	11		
100	12	24	26	12	20	23			

* Based only on the current-carrying capacity of the branch circuit. In general, it is the practice in new wiring installations to "underload" to prevent excessive voltage drop (see Table 17).

The line current that a given ballast will draw can also be calculated by knowing the rated watts loss and the power factor at the nominal voltage rating. The general formula is

Total watts
= (nominal voltage rating of ballasts)(line current)(power factor)

The total watts is equal to the lamp watts plus the ballast watts loss, and the nominal voltage is 118, 208, or 236 volts depending on the circuit voltage of the ballast (110–125, 199–216, or 220–250 volts), whereas the power factor is that of the ballast and the lamp or lamps it controls. All these data are found in Tables 7, 8, and 9.

For example, a 20-watt single-lamp high power factor ballast will have a watts loss of approximately 4.5 at the rated lamp watts input and at 118 volts. The approximate line current drawn by such a ballast would be

$$\frac{20 + 4.5}{(118)(0.95)} = 0.23 \text{ line ampere}$$

For a two-lamp 110–125-volt 40-watt ballast, these figures would be

$$\frac{80 + 15.5}{(118)(0.95)} = 0.95 \text{ line ampere}$$

The total current in a particular circuit between the panel box or feeder and the first ballast on the circuit is equal to the sum of all the line amperes of the ballasts on that circuit.[1] Of course, the current-carrying capacity of a particular branch feeder or circuit is determined by the new National Electrical Code, and it is suggested that this new Code be carefully studied before making fluorescent wiring plans.

Location of Power-factor Correction Capacitors.—In Table 11 are given some data on correcting power factor by the use of small capacitors especially designed for fluorescent systems. It is strongly recommended that capacitors of this type be used to correct the power factor of installations involving single-lamp low power-factor ballasts to reduce the current required, to enable the application of more fluorescent lamps on a given wiring capacity, and to meet existing power-factor regulations. Only by having a high power factor can the customer realize all the higher footcandle level possibilities that these new sources offer.

In addition, reducing the line current by appropriate power-factor correction also lowers the wattage loss in the wiring system itself and improves the voltage at the ballasts. The wattage loss in the wiring system is often neglected in lighting calculations, but actually it is of considerable importance. This energy loss in a 100 per cent power-factor system is only one-fourth that of a comparable wattage load at 50 per cent power factor. The meter registers the kilowatt-hours lost in the wiring system just as it does those actually used in producing light.

The point of application of the capacitor is important, for the effect of reducing current demand is felt from the point where the capacitor is applied back through the entire wiring system in the direction of the supply. Suppose, for example, that one large capacitor was applied at the distribution panel at the service entrance. This arrangement would reduce the current demand on the utility power lines and would meet requirements of high power factor where such regulations exist. However, locating the capacitor in such a fashion would give no benefit to the lamp circuits (assuming, of course, that uncorrected power-factor ballasts are involved or that it is desired to improve the power

[1] The assumption is that ballasts having the same power factor are used throughout the branch circuit.

factor of thermal or magnetic auxiliaries in installations made before the availability of high power-factor two-lamp ballasts).

To obtain the minimum current at all points in the wiring circuit, the capacitor should be applied as near the center of the load as possible. For example, if one capacitor is used for each group of six lamps, three of the lamps should be connected between the capacitor and the power switch. If one capacitor

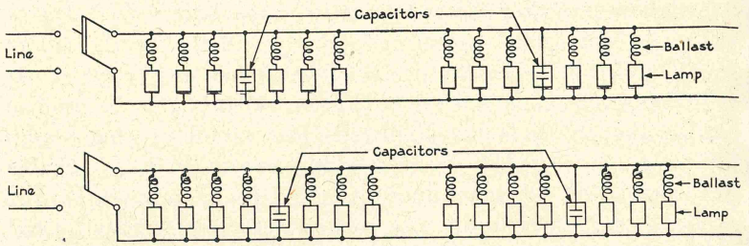


FIG. 59.—The location of capacitor banks for the power-factor correction of a group of an even number of lamps (above) and for an odd number of lamps (below).

is used for each group of an odd number of lamps, say seven, four of the lamps should be connected between the capacitor and the power switch. Where Table 11 shows the need for two or more capacitors in parallel to supply the needed power-factor correction, this bank of capacitors should be located as nearly as possible to the load centers. Figure 59 shows the proper location of capacitors where groups of an odd or an even number of lamps are involved.

TABLE 16.—CAPACITOR DISCHARGE RESISTANCES*

Capacitor Rating, Mf.	Resistor Rating
4.75	5.0 megohms ½ watt
6.5	6.5 megohms ½ watt
11	4.0 megohms ½ watt
17.5	1.5 megohms ½ watt
28	1.5 megohms ½ watt

* Resistor is required only where automatic discharging is not provided by the circuit.

These capacitors usually do not require a discharge device, for they are normally used in parallel with fluorescent lamps having auxiliary equipments that automatically discharge the capacitors when power is switched off. If, however, capacitors are used for some application where automatic discharging is not provided by the circuit, a special means of discharging is necessary. The recommended method is to install a resistor across

the leads of the capacitor. The rating of the resistor recommended in such cases is given in Table 16.

Connecting the Ballasts.—In those instances where the fluorescent fixtures are wired "on the job" or in the case of some continuous-row installations, etc., where the actual circuit connections are made at the point of installation (Fig. 60), considerable time can be saved by the wiring man and future

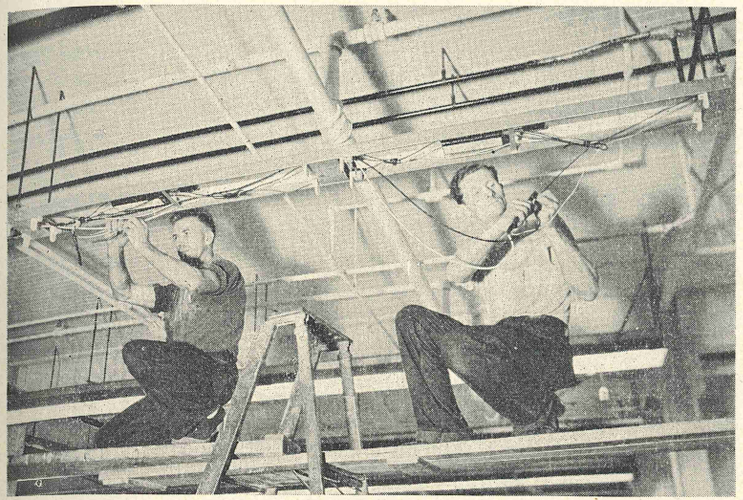


FIG. 60.—Where fixtures are wired "on the job," as in this continuous-row installation, it helps to know exactly where each colored ballast lead should be connected.

trouble avoided if the color coding of the ballast involved is thoroughly understood. Generally, ballast manufacturers follow the same color coding in their ballast lead wires, which simplifies the problem for the maintenance man. For example, 40-watt two-lamp ballasts using separate starting compensators have one black lead wire. This wire is connected to one side of the line only (all the way down the wiring channel in continuous-row installations). The white lead wire from such a ballast goes to the other side of the line and also to one end of each of the two lamps. The red lead wire of the two-lamp ballasts is the connection to the leading power-factor branch of the circuit, and the separate starting compensator is connected in series with the starter of the lamp wired to this red ballast lead. The blue lead wire of two-lamp ballasts goes to the lagging lamp.

Study of the various circuit diagrams (Figs. 28 through 38) will show the details of connecting any of the standard ballasts. The procedure outlined in the foregoing paragraph will indicate the simple relationships between the component parts of fluorescent circuits and will disclose to the wiring technician what simple short cuts can be made on the job.

At least one large ballast manufacturer has also color-coded ballast labels to assist in the identification of ballast voltage ratings. One color of label is used for 110–125-volt ballasts, another color for 199–216-volt ballasts, and still a third for 220–250-volt ballasts. Such a system has, of course, considerable value especially where ballasts must be quickly selected for voltage range. Color-coded ballast labels also greatly simplify the important task of checking the voltage rating of ballasts in fluorescent luminaries.

Wiring Standards.—Many buildings wired 15 or more years ago have a capacity of only 2 watts per sq. ft. or so.[1] A capacity of 2 watts per sq. ft. will provide for illumination levels of 10 to 15 footcandles of filament lighting in industrial areas or around 8 to 12 footcandles in commercial areas with standard reflecting equipment. Possible illumination levels of fluorescent lighting on this wiring capacity would, of course, be considerably more than the values mentioned provided high power-factor auxiliary equipments were employed. For example, if the lighting equipment consisted of industrial fluorescent reflectors of the type in common use (two 40-watt lamps on a two-lamp ballast—about 100 watts over all), a wiring capacity of 2 watts per sq. ft. would allow the use of one such reflector for every 50 sq. ft. of floor area. If 40-watt white fluorescent lamps were employed, the average illumination level in service for such a spacing would be 35 to 40 footcandles in a typical factory area. The illumination level might be only about 50 per cent of the above for 2 watts per sq. ft. in the average commercial interior when using fluorescent equipment appropriate for that service. It is obvious that 2 watts per sq. ft. is insufficient—that rewiring will often be necessary if high-quality fluorescent installations of the footcandle levels needed by present production and merchandising efforts are to

[1] The "watts per square foot" is simply an indication of the current-carrying capacity of the copper wire installed for each square foot of floor area in the installation.

be installed. The new thin-wall wires can now be used in rewiring programs to secure a wiring capacity of double the watts per square foot provided by the copper being replaced.

Those who will install well-engineered fluorescent installations will carefully consider the various aspects of the wiring problem. Not only must current-carrying capacity limits as specified by the new National Electric Code be followed, but the voltage drop must be kept to a satisfactory value in any wiring or rewiring program. Well-founded recommendations in the past have quoted the acceptable voltage drop to be 2 volts on branch circuits, and, because of the many ways line voltage affects the operation and performance of fluorescent lamps, there is every reason to believe that this maximum of 2 volts drop is an appropriate one for fluorescent installations. Table 17 indicates

TABLE 17.—WIRE SIZE REQUIRED
Computed for Maximum of 2-volt Drop on Two-wire 115-volt Circuits

Load per circuit, watts	Current 115-volt circuit, amperes	Length of run (panel box to load center), feet																	
		30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
500	4.3	14	14	14	14	14	14	12	12	12	12	12	12	10	10	10	10	10	10
600	5.2	14	14	14	14	14	12	12	12	12	10	10	10	10	10	10	10	8	8
700	6.1	14	14	14	14	12	12	12	10	10	10	10	10	10	8	8	8	8	8
800	7.0	14	14	14	12	12	12	10	10	10	10	10	8	8	8	8	8	8	8
900	7.8	14	14	12	12	12	10	10	10	10	8	8	8	8	8	8	8	8	6
1000	8.7	14	14	12	12	10	10	10	10	10	8	8	8	8	8	8	6	6	6
1200	10.4	14	12	12	10	10	10	10	8	8	8	8	8	6	6	6	6	6	6
1400	12.2	14	12	10	10	10	8	8	8	8	8	6	6	6	6	6	6	6	6
1600	13.9	12	12	10	10	8	8	8	8	6	6	6	6	6	6	6	6	4	4
1800	15.7	12	10	10	10	8	8	8	6	6	6	6	6	6	4	4	4	4	4
2000	17.4	12	10	10	8	8	8	6	6	6	6	6	6	4	4	4	4	4	4
2200	19.1	12	10	10	8	8	8	6	6	6	6	6	4	4	4	4	4	4	2
2400	20.9	10	10	8	8	8	6	6	6	6	6	4	4	4	4	4	4	2	2
2600	22.6	10	10	8	8	6	6	6	6	4	4	4	4	4	4	4	4	2	2
2800	24.3	10	8	8	8	6	6	6	6	4	4	4	4	4	4	4	2	2	2
3000	26.1	10	8	8	6	6	6	6	6	4	4	4	4	4	4	2	2	2	2
3500	30.4	10	8	8	6	6	6	4	4	4	4	2	2	2	2	2	2	2	2
4000	34.8	8	8	6	6	6	4	4	4	4	2	2	2	2	2	2	1	1	1
4500	39.1	8	6	6	6	4	4	4	2	2	2	2	2	2	1	1	1	1	1

the wire sizes required for a minimum of 2 volts drop on two-wire 120-volt circuits for various wattage loads and lengths of

run. Certainly high power factor looms up as an important user benefit in terms of adhering to his installed wiring capacity.

Table 18 shows the current that results in a 2 per cent voltage drop (2.4 volts) of a 50-ft. (100 ft. of electrical length) 120-volt

TABLE 18.—VOLTAGE DROP AND WIRING UTILIZATION

Wire size	Resistance, ohms per 100 ft. at 40°C.	Amperes to give 2.4 volts drop (2 per cent of 120 volts)	Allowable current capacity of Type SN wire	Number of wires in conduit*	Allowable current capacity used, per cent
No. 14	0.273	8.8	14.4	6	61
No. 12	0.171	14.0	18.4	6	76
No. 10	0.108	22.2	31.0	3	72
No. 8	0.068	35.4	41.0	3	86

* Taken as typical of what might be expected in branch circuits with ½- or ¾-in. pipe.

circuit using various wire sizes. The table also indicates the *allowable* current-carrying capacity of type SN wire (synthetic thin-wall insulation permissible for rewiring only) used in accordance with the new Code. The last column shows the percentage of allowable current capacity actually used if the voltage drop is held to 2 per cent. Some customers and contractors might prefer to utilize the current-carrying capacity of the wiring system to its maximum at the expense of voltage drop, but the maintenance of a 2 per cent limit on voltage drop will have its eventual reward in terms of wattage saved (less wiring loss) and/or in improved fluorescent-lamp performance and operation.

It will be obvious from Table 18 that if the run were 100 ft. long (200 ft. of electrical length) the current value would be correspondingly reduced for the same voltage drop and the wattage through the conduits would be considerably less than half the wattages represented by the allowable maximum current-carrying capacities.

Although the efficiency of fluorescent lamps makes possible the comfortable and economical attainment of the higher foot-candle levels, it is still desirable to provide additional current-carrying capacity for future increases in lighting load. In

general, extra capacity can be initially installed at but a fraction of the cost of doing the same job later.

New Wiring Materials.—By now, most contractors are thoroughly familiar with the 1940 National Electrical Code and know about the new building wires, their possibilities, and their Code limitations. Everyone interested in fluorescent lighting should make it a point to become thoroughly versed in the new Code so that constructive advice can be given to the customer. Wiring-capacity problems are frequent, even with fluorescent lighting.

One of the outstanding features of the new Code is the allowance of higher conduit fill plus small-diameter wire in *rewiring programs*. This, of course, makes possible a considerable permissible increase in capacity without the high cost of tearing out old conduits and installing larger pipe sizes. Even when the 2 per cent voltage-drop limit is adhered to, considerable increases in capacity are possible with the new small-diameter wiring materials.

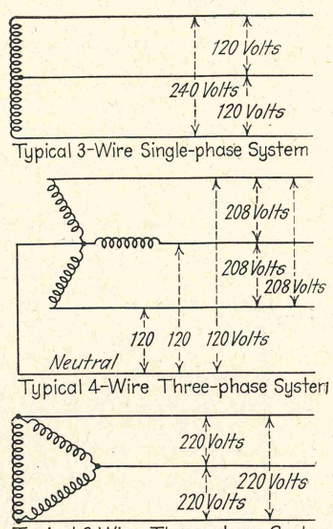


FIG. 61.—Typical distribution circuits showing how it is sometimes possible to utilize fluorescent ballasts designed for higher voltages.

Voltage Selection.—It is well-known that wattage capacities can be doubled by using a voltage distribution of 240 instead of 120 volts. Or, for a given wattage load, the voltage drop can be halved and the energy loss in the wiring cut to one-fourth if such high voltage distribution is employed.

Because fluorescent ballasts for 30-, 40-, and 100-watt lamps are available in three voltage ranges (110–125, 199–216, and 220–250 volts), it is frequently possible to utilize higher voltage distribution and obtain the advantages above mentioned. On a three-wire single-phase 120-volt system, 240 volts is available and 220–250 volt ballasts can be employed. If a four-wire three-phase system of 120 volts to neutral is available, 208 volts can be obtained from phase to phase. Ballasts rated at 199–216

volts would be used in such cases, and where three-wire three-phase systems of 220 or 230 volts are available, the 220–250-volt ballasts are appropriate. Figure 61 illustrates these three possibilities.

There is also less ballast watts loss when higher voltage ballasts are used than with 110–125-volt equipment. This effects a slight improvement in over-all efficiency of light production.

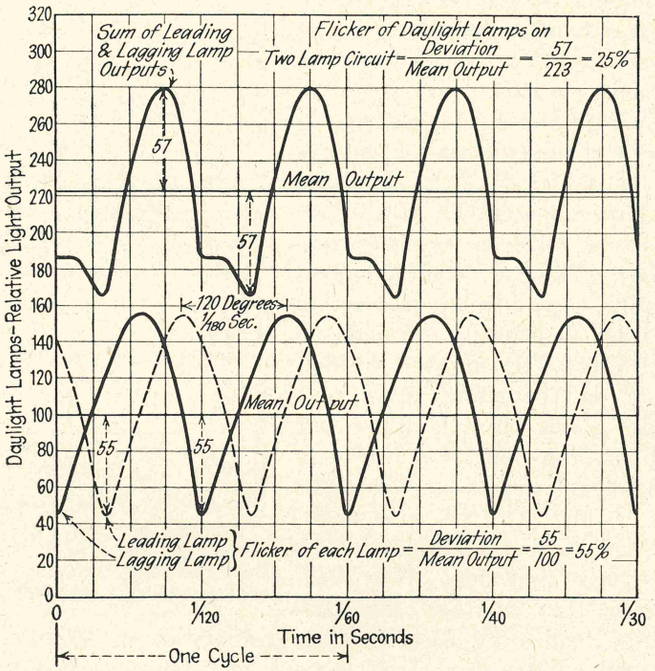


FIG. 62.—The two-lamp ballast circuit considerably reduces stroboscopic effect as shown here.

Methods of Reducing Stroboscopic Effect.—The most satisfactory method of minimizing annoyance due to normal flicker of fluorescent lamps when operated on alternating-current circuits is the use of two-lamp ballasts. As has been previously explained (Chap. II), the series capacitor in the leading branch of the two-lamp circuit produces a power factor of about 50 per cent leading, which means that the current wave reaches its maximum 60 deg. ahead of the voltage wave. The other lamp is

ballasted by inductance alone and has a power factor of about 50 per cent lagging, which means that the peak of its current wave will be reached 60 deg. after the peak of the voltage wave. Since the variations in light output closely follow those of lamp current, the maximum light output of the leading lamp will be

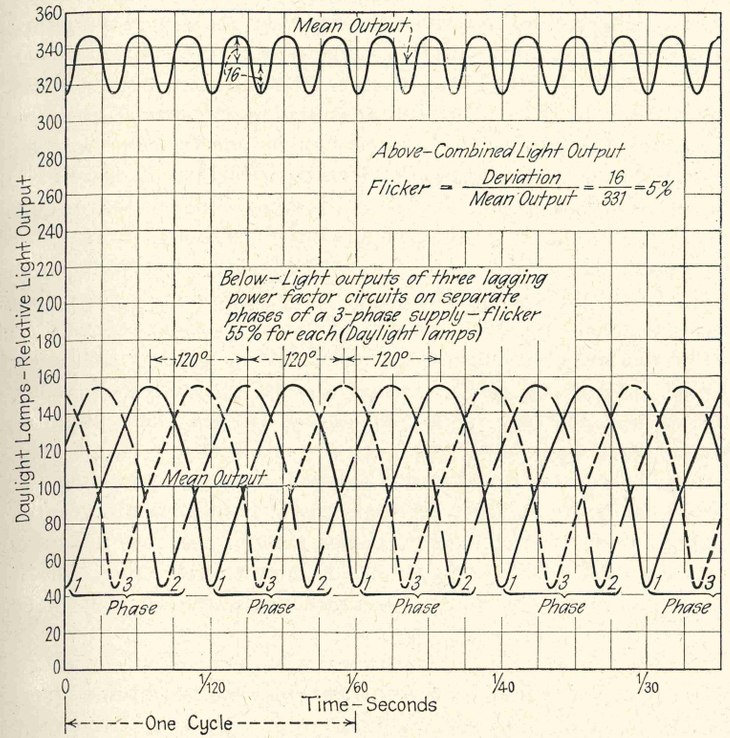


FIG. 63.—Stroboscopic effect can be minimized on alternating-current circuits by connecting alternate lamps or units to the individual phases of a three-phase distribution system.

about 120 deg. ($\frac{1}{180}$ sec. for 60-cycle circuits) ahead of the maximum light output of the lagging lamp. This means that the maximum light output of one lamp will overlap the minimum light output of the other lamp and the flicker will be very much reduced (Fig. 62 and Table 13).

The other method of reducing flicker, or stroboscopic effect, from fluorescent lamps is to operate them on separate phases of

a three-phase system. Thus, the light outputs of lamps on the three different phases are each "separated" by 120 deg. and the minimum light outputs do not occur simultaneously. To obtain the greatest reduction in flicker by such a method, adjacent lamps, or at least adjacent luminaires, should be on different phases. This obviously could complicate the wiring to some extent. Figure 63 shows how the light output can be smoothed out by operation on the different phases of a three-phase system.

State and Utility Power-factor Regulations.—State utility commissions have recognized that it is more expensive for power companies to serve low power-factor loads than the same wattage at high power factor and have permitted (or even directed) the consideration of power factor in making charges for electric energy, especially where large loads are concerned. In fact, the fluorescent lamp has brought the power-factor question so much to the front that some state utility commissions have ruled that fluorescent-lighting systems must have corrected power factor.

The method of taking power factor into account in billing for electric energy of course varies among the different utility companies. In some cases, loads below the specified minimum power factor may be accepted but are charged at a higher rate, usually based on the demand, connected volt-ampere load, or the actual power factor. In some cases, premiums are granted for high power factor; this furnishes a more concrete incentive for correction. The regulations of many state and electric companies, however, actually require correction to a specified definite minimum power factor.

State regulations of this nature may be secured by consulting the state utility commission, and local rules can be obtained from the utility companies serving that area. Of course, the most satisfactory solution is the use of two-lamp ballasts whenever possible.

Calculating the Power Factor of Fixtures Having an Odd Number of Lamps.—Sometimes the question arises as to the over-all power factor of fluorescent fixtures having an odd number of lamps, and where both high power-factor ballasts and uncorrected power-factor ballasts are employed. Suppose, for example, that it is desired to know the over-all power factor of a fluorescent fixture containing two 40-watt lamps operated from a two-lamp ballast and one 40-watt lamp operated from a

single-lamp uncorrected power-factor ballast. The resultant power factor could be obtained by using the following formula:

$$\text{Over-all power factor} = \frac{\text{total wattage consumed}}{(\text{total line current})(\text{line volts})}$$

The total wattage is the wattage consumed by all the lamps plus the watts loss in all the ballasts. The total line current can be determined by an ammeter measurement or can be calculated mathematically.*

For our example, the equation would become

$$\text{Resultant over-all power factor} = \frac{(40 + 40 + 17.5) + (40 + 12)}{(1.53)(118)} = 0.83, \text{ or } 83 \text{ per cent}$$

This method may be applied to a fixture or installation involving any number of lamps where ballasts of different power factors are in parallel.

* See p. 289 in the Appendix for an explanation of the mathematical method used to determine the total line current when ballasts having different power factors are connected in parallel.

CHAPTER V

SERVICE SUGGESTIONS[1]

The Importance of Knowing "Why."—The sweeping acceptance of fluorescent lamps and the rapid introduction of new lamp sizes and control equipments have created a problem of interpreting laboratory test data as they apply to the practical servicing of fluorescent installations. The problem has been general—manufacturers have had to devise radically new techniques and develop new production equipment, fixture designers have been introduced to problems never encountered with filament luminaires, and lighting installation and maintenance personnel have been required to understand all the technical aspects of this radically new light source and the operating problems encountered.

The relative simplicity of servicing a filament-lamp installation is well known. For example, if a filament lamp does not light when current is applied, the one simple, positive conclusion is that the lamp is burnt out or defective. No such conclusions should be made in the case of the fluorescent lamp. Although perfect in all respects, the fluorescent lamp may not start or operate properly through no fault of its design or manufacture. The lamp is but one link in the chain. The proper starting and operation of fluorescent lamps require specially designed auxiliary equipment consisting of ballasts and starters. It is necessary that the design and rating of auxiliary equipments comply with certain specifications which have been established. These specifications are not difficult to meet and are simply safeguards set up to insure proper lamp performance. However, lamp-performance troubles may be encountered if equipments which do not meet these specifications are used.

[1] Much of the information contained in this chapter was originally obtained by L. R. Keiffer of the Nela Park Engineering Department, General Electric Company.

As discussed in Chap. II, the function of the ballast is to deliver the proper voltage and lamp current, one value for starting, another for normal operation. The ballast must also limit the current to the value normally required by the lamp. Similarly, the automatic starter switch must close and open with reliable timing and pass enough current through the filament-type cathodes long enough to preheat these sufficiently for quick and positive starting. The proper performance of these devices, in turn, is dependent upon the customer's voltage being within a certain acceptable range. Further, conditions of use by the customer, such as cold drafts and temperature of surroundings, materially affect starting and operation. Thus it may happen that a normally perfect fluorescent-lamp device may not perform properly because of circumstances entirely within the control of the user himself.

The Contractor's or Installer's Responsibility.—Even though the most efficient inspection procedures are observed in lamp and fixture manufacture which will result in products free from defects, the installer must assume the responsibility for proper electrical connection and workmanship when the lighting equipment is put on the customer's premises. Existing circuits should be checked to determine whether the supply voltage is direct or alternating current, the ballasts within the luminaire should be inspected to make sure that their voltage rating conforms with the nominal circuit voltage at hand, and actual socket voltages should be within the limits prescribed for fluorescent lamps. It is only "the man on the job" who can say with assurance what the actual operating conditions are.

If the installer also assembles and wires the luminaires, he is responsible for using approved wiring materials and methods and for making the proper circuit connections within the fixture.

Educating the User.—It is important that the contractor or person making the lighting installation educate the customer regarding the proper maintenance of his fluorescent lamps and indicate his responsibility in the proper performance and functioning of the new lighting system. Just as we have learned to know that automobile tires should be inflated to proper pressure to insure satisfactory tire safety and life performance, so also a knowledge on the part of all concerned of the factors attending the performance of fluorescent lamps is necessary to enable satis-

factory service to be obtained by the user and to enable him to take corrective measures in cases where unusual operating conditions prevail.

For example, the user must appreciate that the electrical circuits on his premises must deliver the necessary voltage conditions within the prescribed limits. He should know that temperature is a factor in this new lighting. He must understand the principles of maintenance, such as prompt lamp and starter replacement, keeping lamps and fixtures clean, and the value of washing and painting walls and ceilings for good maintenance of lighting levels. Many factors concerning lamp life are within the control of the owner; one important customer responsibility is the elimination of lamp blinking by (1) promptly removing lamp or starter involved or (2) using No-Blink starters which remove the starter element from the circuit if the lamp fails to light after a reasonable number of attempts. (See description of this type of starter in Chap. II.)

Average Lamp Life.—Normal failure of fluorescent lamps is due, not to breakage of the filament and the consequent interrupting of the electrical circuit as in the case of an incandescent lamp, but to the gradual dissipation of the active electron-emitting material on the cathodes. The more common sizes of fluorescent lamps have a rated life of 2500 hr. Like filament lamps, it is not unusual for some fluorescent lamps to fail after a few hundred hours, whereas others may last 4000 or 5000 hr. to balance out the normal early failures.

A mortality curve of fluorescent lamps is shown in Fig. 64. It will be noted that the curve is quite similar to those published for filament lamps. Although the fluorescent lamp has been too recently introduced to establish a final mortality curve, an average trend obtained from examination of several hundred lamps is shown, where lamps are started no oftener than once every three or four burning hours and are tested under known and controlled conditions. Mortality curves, in general, for lamps and most other renewal products are similar in form to the curve shown. Attention is called to the fact that well-established sampling fluctuation laws applying to this general type "average performance" show that the frequency and extent of irregularities and departures from average performance increases as the number of lamps decreases in groups under

examination. In other words, if there were a small number of lamps involved in an installation, the percentage of lamps remaining at a given percentage of average life might be considerably different than indicated by the curve, which represents a larger group.

The average life of fluorescent lamps is known in some cases to be affected to quite some degree by the number of lamp starts and starter characteristics, the life usually being lengthened as the frequency of starts for a given burning period is decreased. This results because the active compound of barium and stron-

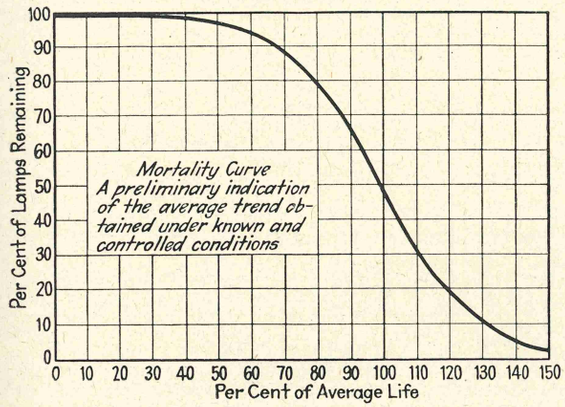


FIG. 64.—The fluorescent-lamp mortality curve, a preliminary indication of the average trend based on the examination of several hundred lamps.

tium with which fluorescent cathodes are coated is more actively dissipated during starting than during normal operation. Therefore, a longer life will be obtained if the lamps are allowed to operate continuously instead of being turned on and off frequently. However, rated life should be obtained on the average if lamps are operated for normal periods of 3 or 4 hr. between starts. Other factors, such as wave form of supply, characteristics of operating circuits, and ambient temperatures, may also affect the life as well as other performance characteristics of these lamps.

Normal Lamp Failure.—When the active cathode material is used up at either one end or both ends, the lamps will no longer operate but will simply blink on and off, and there may be quite

a shimmering effect of the lighting during the period that it remains lighted. Most fluorescent lamps fail in this manner.

In new lamps, the cathodes are completely coated with a white paste of activating material. As the lamp proceeds through life, this active material disappears, starting from the side of the cathode connected to the circuit (the other side of each cathode is connected to the starter). Near the end of life, active material will remain at the end of the cathode connected to the starter, and at final deactivation, the cathodes are clean and shiny.

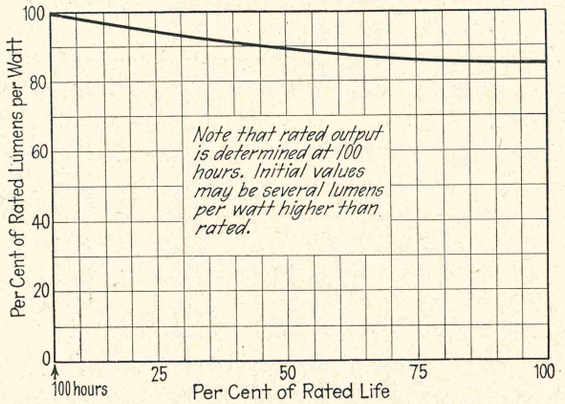


FIG. 65.—The light output and luminous efficiency of fluorescent lamps falls off gradually during life as indicated by this curve. The lumen maintenance is comparable to that of filament lamps. However, the wattage of fluorescent lamps is practically constant throughout life.

Deactivation is indicated by a deep orange-colored glow of a heated cathode. This may appear at only one end, since it is possible for one cathode to become deactivated before the other owing to the possible "rectifier" action of glow-switch starters.

Normal Depreciation in Light Output.—Fluorescent lamps blacken rather uniformly throughout the length of the tube during life. This is usually not very noticeable unless a lamp that has burned for a considerable time is compared with a new one in front of a light source. However, this light uniform blackening more than any other cause results in a depreciation of light output during life.

The light output decreases rather rapidly during the first 100 hr. of operation, and the loss may amount to as much as 10 per cent. In fact, the depreciation in light output during the first

100 hr. is about as much as during the following thousand hours. Therefore, the 100-hr. value is used for rating purposes. The light output may depreciate another 15 per cent on the average for average operating conditions by the end of rated life. The light output during life averages approximately 90 per cent of the 100-hr. value. Figure 65 shows the lumen maintenance curve throughout life.

Since the output from new lamps is about 10 per cent greater than published values, footcandle readings taken shortly after making a complete installation of new lamps may be somewhat higher than the illumination levels designed for on the basis of rated lumen output. The effect of this and other factors in predicting "in service" illumination levels will be discussed in Chap. VII.

There are a number of factors to be considered in checking depreciation of the light output under service conditions. For example, remember that the ballast delivers a slightly lower output when heated as compared with its initial, or cold, value. Too, if heat is confined around the lamp, the light output may be appreciably reduced. Low temperature and drafts will change the light output over a wide range as has been previously explained. An accumulation of dust or dirt on the lamp and fixture and on painted walls and ceilings can obviously reduce the illumination considerably. Accurate measurements of depreciation from the lamp standpoint usually necessitate removing the lamp and obtaining readings in a laboratory photometer under conditions that have been duplicated for "before" and "after" periods of operation.

Lamp Appearance.—At the end of life, the lamps usually show a dense blackening at either one end or both ends. Also, there may be dark rings slightly brownish in color at one end or both ends. However, on the average, there should be little indication of blackening or rings during the first 500 hr. of operation. Any unusual appearance or performance from a quality standpoint should develop during the first 200 hr. of service.

Rings.—Rings or bands slightly brownish in color develop at either end or at both ends. These are usually about ¾ in. wide, rather clear-cut (on the edge nearer the base), and located about 2 in. from the base at either end or at both ends. Such rings are usually a natural development during life as a result of normal

cathode consumption. A typical case is illustrated in Fig. 66.

Dense Spots near Ends.—Near the end of life, some lamps develop a dense black spot about ½ in. wide extending almost halfway around the lamp and centering about 1 in. from the base.

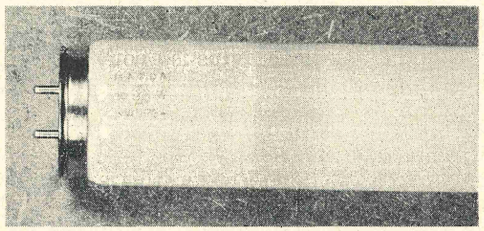


FIG. 66.—A typical ring near the end of a fluorescent lamp—a result of normal electrode consumption.

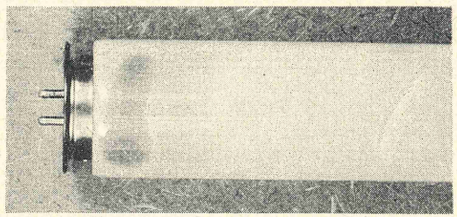


FIG. 67.—Small, dense spots near the end of a fluorescent lamp often develop normally late in lamp life.

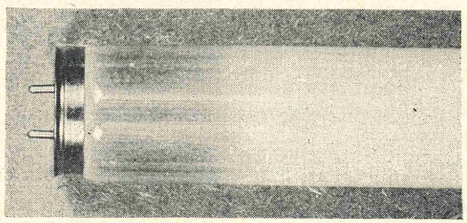


FIG. 68.—Typical general blackening at the end of a fluorescent lamp.

This is quite normal; but if such a spot develops early in life, it is an indication of excessive starting or operating current. This may be due to a ballast off-rating or to an unusually high circuit voltage. Such a dense spot is shown in Fig. 67.

Normal End Blackening.—The familiar normal end blackening of fluorescent lamps is illustrated in Fig. 68. Such blackening

may develop either at one end or at both ends and usually extends from the base for a distance of 2 or 3 in. It is simply a collection of the cathode coating gradually lost during life.

Mercury Deposits.—Normal end blackening should not be confused with a mercury deposit which sometimes condenses around the bulb at the ends. This mercury condensation appears to be more common with the 1-in. diameter lamps than with the 1½-in. sizes. It is often visible on new lamps but should evaporate after the lamp has been in operation for some time. However, it may reappear later when the lamp cools.

Frequently, dark streaks appear lengthwise of the tube due to small globules of mercury collecting on the lower (or cooler) part of the lamp. In fact, mercury may condense in any place on the tube if a cool object is allowed to lie against it for a short period. Such spots near the center section may not evaporate again. When condensation occurs in this manner, rotating the lamp 180 deg. in the lampholders may give a more favorable position for evaporation or may place the spot in a less conspicuous place from an appearance standpoint.

Early End Blackening.—Heavy end blackening early in life means that the active material on the electrodes is being sputtered off too rapidly and indicates improper operating conditions.

These may be as follows:

1. High or low voltage. For best results, circuit voltage should be within the ballast rating.

2. Loose contacts (most likely at the lampholder) causing lamps to blink on and off. Remedy: Lampholders should be rigidly mounted and properly spaced. See that lamps are securely seated in lampholders.

3. Improperly designed ballasts or ballast outside specification limits. Remedy: The use of ballasts approved by the Electrical Testing Laboratories will usually eliminate trouble of this nature.

4. Defective or worn-out starter causing (1) lamp to blink on and off, (2) prolonged flashing of the lamp at each start, or (3) end of the lamp to remain lighted over a period of time. Remedy: Replace with a new starter.

5. Omission of the starting compensator in the leading branch of a two-lamp ballast circuits for 15-, 20-, 30-, or 40-watt lamps. Remedy: Install a compensator.

Starting Difficulties.—Starting difficulties may be due to a number of other causes than the starter itself. In general, any difficulty in starting may result in premature end blackening and short lamp life. In fact, lamp life is controlled to a large extent today by the operation of fluorescent starters. *The quality of the start* is as important as the *number of starts*. Proper preheating (the production of an "end glow" which is a glow discharge around the electrodes and should not be confused with the dull red glow of the heated cathode) is essential for proper lamp performance. For example, the omission of the starting compensator (where required) will cause insufficient cathode preheating when the lamp is started. This "cold" starting is quite likely to result in reduced lamp life. Various causes of starting difficulties are listed below.

Lamp Blinks On and Off.—This may simply be a normal lamp at the point of failure. But if the lamp is new or if it has not been in service long, there are a number of factors that might cause this action. The difficulty may be due to the starter,[1] and this can readily be replaced. It is possible that the lamp may be at fault, and lamp replacement is the next logical step. Changing either the lamp or starter may only temporarily correct the trouble if there is a borderline cause of difficulty for some other reason. The annoyance of blinking lamps may be eliminated by using No-Blink starters in installations employing those sizes of lamps for which such types of starters are available.

Low circuit voltage, low ballast rating, low temperature, and cold drafts may individually cause difficulty of this nature, or several of these conditions may be contributing factors.

If two-lamp ballasts are involved, there is a possibility that the individual starter leads from the two pairs of lampholders have been crisscrossed. When this is the case, the two lamps may start promptly if both starter switches open simultaneously. However, if one lamp starts, the other lamp may blink on and off for a long period of time or may not start at all. This sort of trouble is generally easy to locate, because after one lamp

[1] Glow voltage is an unreliable criterion of glow-switch starter quality. In the laboratory, the test for glow starters is the starting of lamps in the lead circuit of a two-lamp ballast on 105 volts. In the field, such starters should be tested with a lamp, ballast, and voltage combination known to be satisfactory.

starts only one end of the other lamp will light up before the starting effort is made. Also, one lamp will not make a starting effort unless the other is in the lampholder. Thus, by testing each of the two lamps separately, this wiring fault can be easily detected.

Lamp Makes No Starting Effort or Starts Slowly.—Be certain the lamp makes proper contact in the lampholders. The lamp can be checked by testing it in another circuit, as there may be an open circuit in the lamp. It is possible that the starter has reached the end of life and should be replaced.

If necessary, a voltage check should be made from one lampholder to the other. This can be done with a voltmeter or with a test lamp (220 volts, 100 watts). It should be remembered that there are two connections to each lampholder, and but one of these at each lampholder should be alive. Hence, there are four possible ways of checking these contacts to find the two live ones. If no voltage indication can be found, next check the circuit leads to the lampholders. If there is still no voltage indication, check the circuit connections. There is also a remote possibility of an open-circuited ballast.

Ends of Lamp Remain Lighted.—In a new installation it is, of course, possible for the circuit to be incorrectly wired. However, if the installation has been in operation, the trouble may be due to a short-circuited condenser in the starter, or it is possible that the starter-switch contacts are welded together. In either case, it is necessary to replace the starter. Starters that have been in service for some time can fail in this manner. Of course, with short-circuiting types of No-Blink starters, lighted lamp ends may simply indicate that the lamp is inoperative. The situation automatically corrects itself when the lamp is replaced.

The Importance of Making Prompt Remedies.—If the lamp is not operating perfectly, it should not be left connected to the circuit for any considerable length of time. A lamp blinking on and off may cause more heating in the ballasts than is the case when the lamp is operating normally, which may result in injury to the ballast if allowed to continue for an indefinite period. If the starter is at fault and causes the lamp to blink on and off, this may result in injury to the lamps from a life standpoint. If the lamp has reached the end of life and blinks on and off, the starting

effort can take considerable life from the starter. Replacement with No-Blink starters will improve the situation because such switches will themselves last longer.

It is also undesirable from a ballast wattage loss standpoint to leave starters in the circuit which have welded or stuck contacts. Tests on a 40-watt 110–125-volt two-lamp ballast showed that the ballast loss was 18 per cent above normal with the lagging lamp burning normally and the leading lamp starter stuck. Reversing the situation (lagging lamp starter stuck), the ballast loss was 48 per cent above normal, and with both starters stuck the wattage loss in the ballast was 59 per cent more, or 26 watts against a normal of 17. A single lamp can be operated from a two-lamp ballast without harm if the other lampholders are empty. The above test showed the wattage loss in the ballast to be 65 per cent of the normal operation with both lamps.

It is realized that frequently the mounting height of the fixtures or other characteristics of the installation make it difficult to replace promptly the lamp or starter when a lamp blinks off and on. Certainly No-Blink types of starters should be employed in such cases. Such starters also make practical the group replacement of fluorescent lamps especially for those places where relamping is difficult.

Excessive Under- and Over-voltage.—So-called low- or normal-voltage ballast equipments are designed to give satisfactory lamp performance on circuit voltages of 110 to 125 volts. Such ballasts may in some cases give satisfactory operation on circuits as low as 105 or as high as 130 volts. Similarly, ballasts designed for high-voltage service should operate satisfactorily on circuits from 220 to 250 volts with possible satisfactory operation as low as 210 or as high as 260 volts.

If lamps are used on higher voltages, the operating current becomes excessive and may not only overheat the ballast but also cause premature end blackening and early lamp failure. In the case of excessive undervoltage, the current may be too low for satisfactorily preheating the cathodes and the lamps may flash off and on without starting. Thus, either too high or too low voltage operation is injurious to the lamp.

Special Problems of Direct-current Operation.—As earlier mentioned, special ballast equipment is necessary if fluorescent lamps are to be operated on direct-current circuits, and failures

to provide this special equipment will result in either lamp or ballast failure.

Lamp performance on direct current is inferior in general to that of alternating current operation. As discussed in Chap. III, lamps especially of the 30- and 40-watt sizes may develop a region one-third to one-half the length of the tube which emits very little light under direct-current operation. This condition is called "mercury pumping" and is due to the current flowing continuously in one direction through the tube. Where 30- and 40-watt lamps are used on direct current, reversing switches should be employed, so that the lamp connections can be reversed in the circuit. Reversing these lamps twice a day should practically eliminate this dark region.

Burned-out Cathodes.—Under normal operating conditions, it is very unlikely that sufficient current can be drawn from the ballast to burn out the cathodes. Thus, a trouble of this nature indicates an abnormal circuit or operating condition. Under normal conditions, the ballast even on short circuit will limit the current to a value below that required to burn out a cathode or to cause any fusing of the metal. Cathodes may be examined by viewing the end of the bulb against a pinhole of light which casts a shadow of the cathode on the bulb wall. In this way, it can be observed whether or not the cathode is intact.

There are several common causes of burned-out cathodes. If one end of the lamp is inadvertently placed across a 115-volt circuit, the cathode will generally burn off at both leads with little or no fusing of the metal. Broken lampholders, lampholders with starter sockets attached and surface-mounted on metal, one strand of a stranded conductor touching a grounded fixture, and improper wiring are all common causes of either momentary or definite grounding which can burn out the cathodes. Another common cause is fluorescent-lamp operation on direct current without the necessary additional resistance required.

Flicker.—Differing from the high-frequency stroboscopic effect which is noticeable when observing a fast-moving object under fluorescent lighting and which results from normal variations of light output on alternating current, this discussion refers to the effects commonly known as "spiraling," "swirling,"

"snaking," etc. These forms of flicker are all apparently related as to cause and are thought to be the result of particles of cathode coating material traveling down the arc stream.

A new lamp may flicker in some such manner when first placed in service even though they undergo an aging process in the factory to eliminate this tendency as far as possible. This will usually clear up after the lamp has been operated for a short period or turned on and off a few times. One of the chief causes of flicker is starting the lamp without properly preheating the cathodes; this causes material to be thrown off the cathode, which may promote a recurrence of spiraling. This may be caused by using a starter that is not performing properly, by starting the leading lamp of a two-lamp ballast without a starting compensator, by high-voltage starting, or by starting the lamp with improper auxiliary equipment.

A flicker may suddenly develop at any time during the life of a lamp in normal service and then clear up quickly. Lamps showing a persistent tendency to flicker should be replaced. Further investigation may be necessary if successive lamps continue to develop this condition in the same lampholders.

Color Quality.—Although the many ramifications of the color-quality problem are discussed in Chap. VIII, it is well to emphasize here that great care must be taken to avoid illusions when passing judgment on variations in color, as lamps of exactly the same color may appear quite different in various locations of a given installation. These illusions are usually due to effects from fluorescent lamps of other colors, or to differences in reflector finishes or from colored paints used for decorative purposes. Always interchange the lamps before forming a conclusion where differences of color are involved.

The eye is quite critical in comparing colors, and the light differences within the manufacturing tolerances of both white and daylight lamps may be discernible, although the differences are seldom objectionable. The color of the 3500° white is the most difficult to control from the manufacturing standpoint. The coating is a mixture of two phosphors, one of which is variable in itself and among other things is susceptible to temperature. When the bulb-wall temperature is cool, the appearance is more pinkish than when warm. However, no differences can be detected with the eye in examining groups of blue, green,

or pink lamps, *i.e.*, all blue lamps are almost exact duplicates as to color.

A few 100-watt lamps have shown a greenish appearance at the ends. This is due to the greater green component of the mercury vapor arc at the higher current density at which these lamps operate and to the selective absorption of spots developed during seasoning which increases the percentage of green light emitted. The unlighted appearance of such lamps is normal.

Radio Interference.—It is a well-known fact that the electric sparks generated when a switch is turned on or off will sometimes create a crackling or frying sound in near-by radios. A similar situation exists within a fluorescent lamp, which during its operation on 60-cycle alternating current is automatically turned on and off 120 times per second. The discharge within the tube causes a sputtering or sparking action on the lamp electrodes, thus setting up a continuous series of radio waves, which under some conditions may reach the radio and interfere with reception. There are three ways in which these waves may reach the radio:

1. Direct radiation from the bulb to the radio aerial circuit.
2. Direct radiation from the supply line to the aerial circuit.
3. Line feedback from the lamp through the power line to the radio.

The broadcast frequencies from 550 to 1600 kc. are most affected. In general, interference on short wave is not objectionable because the level of interference energy is low and covers very narrow bands.

The energy radiated by the bulb is dissipated within a few feet and can, therefore, be controlled by proper positioning of the

TABLE 19.—EXTENT OF BULB RADIATION
(Values Are Relative)

Lamp watts	Distance of aerial from lamp				
	2 feet	4 feet	6 feet	8 feet	10 feet
40 or 100	100	47	9	4	0
30	90	43	8	1	0
20	75	35	7	0	0
15	55	26	5	0	0

radio and its aerial. Table 19 shows the extent and comparative amount of bulb radiation for various sizes of fluorescent lamps. It will be seen that, if the aerial is at least 9 ft. from the lamp, interference from bulb radiation is negligible.

In case the radio must remain within the bulb radiation range, it will be necessary to take the following precautions:

1. Connect the aerial to the radio by means of a shielded lead-in wire with the shield grounded, or install a "doublet" type of aerial with twisted pair leads.
2. Provide a good ground for the radio.
3. Locate the aerial proper out of the bulb and line radiation range.

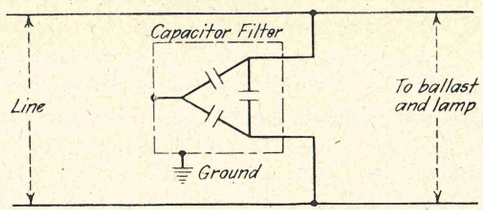


FIG. 69.—The connection diagram for a capacitor type of radio interference filter. Each of the three condensers shown has a capacity of 0.07 mf.

Modern radios equipped with built-in aerials present a more difficult problem when located within the bulb or line radiation range. However, the aerial is directional and can in some cases be adjusted to reduce the interference and provide sufficient signal strength for good reception. Separate aerial and ground connections usually provided on most radios of this design permit the employment of a well-shielded outside aerial.

Interference from line radiation and line feedback can be minimized by the proper application of line filters at each lamp or fixture. Such line filters for the elimination of radio interference from fluorescent lamps are available in two general types, the capacitor and the inductive-capacitor type. The simplest form of filter is the small three-section capacitor, and Fig. 69 shows one such type of filter connected to a typical fluorescent-lamp circuit. Although the capacitor is independent of load and could be used for an unlimited number of lamps, laboratory and field experience show that the best results will be obtained by applying one such capacitor per fixture. In the case of a long

fixture such as a cove, one capacitor should be used for each 8 ft. of lamp length.

In general, the proper use of the capacitor-type filter will reduce line noise approximately 75 per cent. For the cases where it is desirable to eliminate line noise, the inductive-capacitor type is recommended (Fig. 70). Such filters have a definite current rating, indicated on their name plate, and are connected

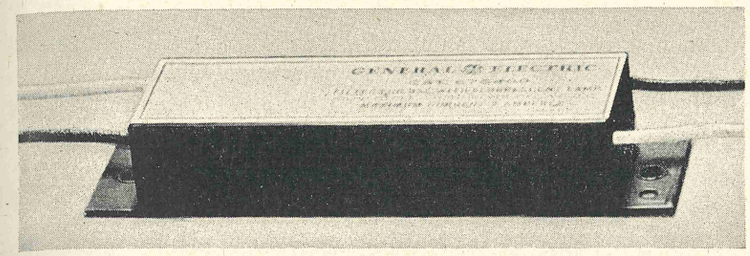


FIG. 70.—A typical inductive-capacitor type of radio interference filter.

as shown in Fig. 71. A filter having a current-carrying capacity of 2 amperes will handle the load of four 40-watt fluorescent lamps.

Where it is necessary to filter each lamp or fixture, the filter should be located as close to the lamps as possible. This precaution should be taken because of line radiation between lamps and filters. When radios located in buildings adjoining the

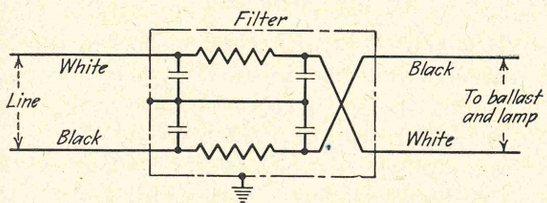


FIG. 71.—The connection diagram of the typical inductive-capacitor filter shown in Fig. 70.

fluorescent installation are receiving line feedback type of interference it is practical to install a single capacitor-type filter at each panel box feeding fluorescent-lamp circuits. Where only one or two radios are located near a fluorescent installation and the aerial circuit has been properly shielded from bulb and line radiation, a single inductive-capacitor filter located at the radio power outlet often will suffice.

In a fluorescent installation such as in a radio-service shop using bench-type units, where a radio is of necessity located near a lamp, it is possible to reduce bulb radiation to a low level by applying a metal screen to the bottom of the fixture. In most cases, the screen would be grounded. Obviously, the screen will absorb some light; it will be necessary to choose the mesh size for a maximum reduction of interference and minimum absorption of light.

There is no measurable line noise from the type RF lamp using the new simplified circuit because of the filtering action of the auxiliary system. The lamp does have some bulb radiation which extends for approximately 6 ft. and corresponds roughly to radiation from the 40-watt standard fluorescent lamp.

Broken Base Insulation.—Even though the base insulation has sufficient strength to withstand reasonable service, if a lamp is dropped or severely bumped on the end, it is possible to break the insulation and make the lamp useless. Both fluorescent-lamp bulbs and bases can be broken by rough handling in shipment.

Base-pin Breakage.—These pins are able to withstand a reasonable pressure without breaking. However, a considerable force can be exerted on them if an attempt is made to turn the lamp in the lampholders without first making certain that the lamps are properly seated. If a lamp does not turn readily when it is being inserted, remove the lamp again and reinsert it into the lampholders.

Broken Cathodes.—The cathodes are short in length and are rigidly constructed and should withstand a considerable amount of rough handling without breakage. However, it is sometimes possible to break them by a severe side blow. To check whether the cathodes are intact, test each end of the lamp separately by connecting the two base pins in series with a 60-watt 115-volt filament lamp on a 115-volt circuit. If the cathodes are intact, the filament of the lamp will light and the end of the fluorescent lamp will glow. This test not only verifies the continuity of the cathode circuit, but the glow also indicates the presence of active electrons. Absence of the glow, even though the cathode heats, is an indication of a lamp that has leaked air.

The 60-watt filament test lamp should be used with lamps from 14- to the 40-watt sizes. For the small T-5 size miniature fluorescent lamps, use a 25-watt 115-volt test lamp, and for the

65- and 100-watt sizes, use a 200-watt 115-volt test lamp. The purpose of the several sizes of test lamps is to limit the current to the values for which the cathodes are designed.

Cathode testers are commercially available and can be effectively used in field servicing work and in shop testing. Figure 72 shows several devices of this type.

RF Servicing.—Because the operating and maintenance principles of RF lamps are somewhat different than those of standard fluorescent lamps, instruction sheets have been packed with the RF units which give the essential information regarding assembly, hanging, installation, wiring, fixture connections, etc. Since in the simplified RF circuit there is no starting switch (in fact, no

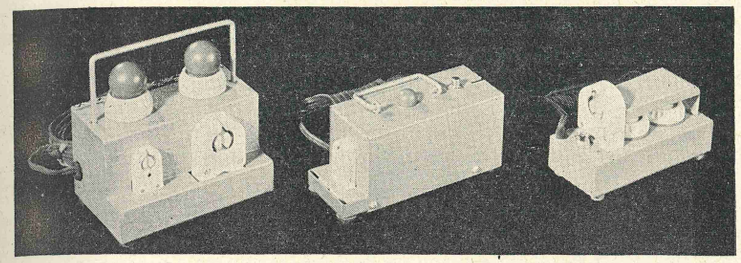


FIG. 72.—Three types of portable fluorescent-lamp cathode testers.

moving parts of any kind), the failure of a lamp to operate once the fixture is properly installed and the power turned on can have but two causes:

1. Interruption of the supply voltage—check wiring, supply switch, fuses, and plug.
2. Lamp becomes inoperative and should be replaced with supply line switch off. Failure due to:

   a. Cathode deactivation. In early stages of deactivation, the lamp may go out and try to relight. In final stages, there will be a weak glow at the anode and a red glow at the cathode.
   b. Loss of vacuum in lamp. When air has leaked in, the lamps will show usual red cathode glow but there will be no glow at the anode.

If RF lamps flicker for any appreciable length of time when power is turned on, the supply voltage is probably too low.

Fluorescent-lamp and Auxiliary-equipment Testing in the Shop.—Several units are commercially available for testing fluorescent lamps, ballasts, starters, luminaire circuits, etc. Similar equipment can also be built up personally—many of the comments in this chapter regarding possible troubles will help in the construction of such an outfit. A study of the wiring diagrams in Chap. II will indicate the accessory equipment necessary to make shop tests of the whole range of fluorescent lamps, ballasts, starters, etc.

Perhaps the most simple setup is to mount lampholders for the different lengths and sizes of lamps on the shop wall or some other vertical panel. The ballasts can be located behind the panel with the starter sockets so placed that starters can be changed without removing the lamp. It is desirable to incorporate a manual starting switch in the test circuit and an ammeter and voltmeter for measuring lamp current and lamp voltage. If these meters are properly selected, it will be possible to use them in checking most of the lamp sizes, in which case only one set of meters (with a suitable switching arrangement) is needed.

A few other pieces of equipment will also be helpful in testing lamps in the shop. A high-frequency coil with a suitable metal electrode can be used to test quickly a group of lamps for air leakage. A lamp that fails to glow when so tested can be removed from the group for further inspection (usually a crack at the junction of glass tube and base). Another helpful device is the small "pinhole" projection system by which the image of the cathode can be projected on the coating of the tube. The cathodes of all but red fluorescent lamps and lamps quite black at the end can be examined in this manner, though it may be necessary to darken the room to test gold lamps because of the coating density. A cathode circuit-continuity tester has already been mentioned.

If a lamp flashes off and on with a starter but starts with a manual switch, it is likely that the lamp is high in voltage rating (the voltage across the lamp during normal operation). Of course there are slight manufacturing tolerances on lamp voltage. The values given in Table 3 are the "rating centers" designed to deliver rated lamp watts at a line voltage centered at the ballast rating and under other definite standard conditions. New lamps should have voltages very close to those rated values. It

should be remembered, however, that (1) the lamp voltage immediately after starting may be 10 to 15 volts higher than the final constant value, (2) the lamp voltage *goes up* (*a*) as the primary voltage goes down, (*b*) as the temperature goes below 80°F., and (*c*) with ballasts of low wattage output.

The open-circuit voltage (measured across empty lampholders with a voltmeter) is the same as the supply voltage for series-choke types of ballasts (see Figs. 28 through 38). For auto-transformer types of 30- and 40-volt 110–125-volt ballasts, the open-circuit voltage should be about 200 volts at 118 volts on the primary. The open-circuit voltage will vary in direct proportion to the primary voltage.

The starting or cathode preheating current at the ballast design center supply voltage should not exceed the values shown in Table 20. In general, the value of starting current

TABLE 20.—MAXIMUM STARTING CURRENTS

Lamp Watts	Maximum Starting Amperes
6(T-5)	0.25
8(T-5)	0.30
14(T-12)	0.65
15(T-8)	0.65
15(T-12)	0.65
20(T-12)	0.65
30(T-8)	0.65
40(T-12)	0.75
65(T-17)	2.20
100(T-17)	2.20

should be about 40 per cent greater than the rated lamp current, although this depends on the time allowed by the starter for preheating. Investigations of cathode preheating requirements indicate that heating is proportional to the product: preheating time multiplied by the square of the preheating current. Therefore, if the current is low, greater time will be required, and vice versa.

Testing in the Field.—Some of the fluorescent-lamp test equipments now on the market are sufficiently portable for field work. Figure 73 shows one such test kit used to check fluorescent-lamp and starter performance in service.

As previously mentioned, the lamp cathode heating-circuit continuity, the condition of the cathode as regards electron-emissive material, and the absence of air in the lamp can be checked by a simple portable tester. Such equipment can be used to diagnose many of the purely lamp complaints.

Since many of the fluorescent maintenance problems involve starting difficulty, the information on this subject found in Chap.

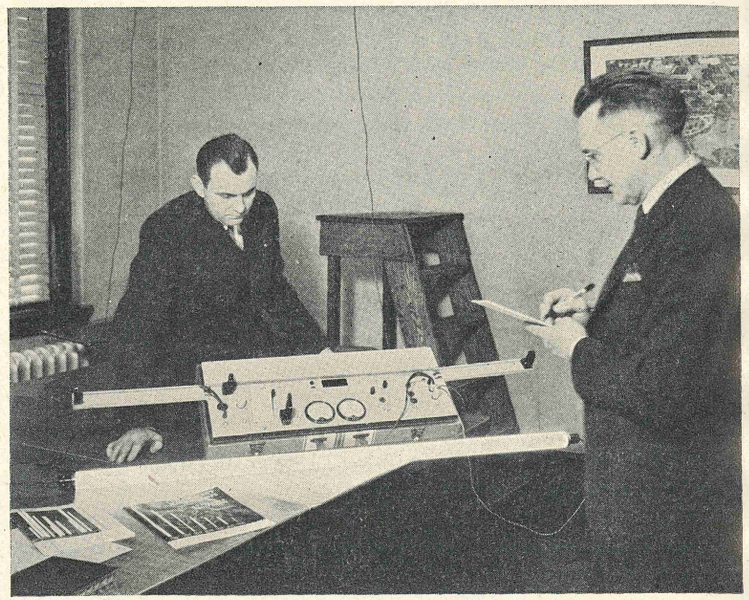


FIG. 73.—A portable fluorescent lamp test kit can be used to check lamp and starter performance in service.

IV should be especially well-known to those doing fluorescent servicing work. Table 21, which summarizes the symptoms, causes, and remedies, will also be helpful in this regard.

TABLE 21.—SUMMARY OF FLUORESCENT SERVICE SUGGESTIONS

Symptoms

Normal End of Life.—Lamp will not operate; or flashes momentarily then goes out; or blinks on and off, perhaps with shimmering effect; ends probably blackened (1*a*).

End Blackening.—Dense blackening at one end or both, extending 2 to 3 in. from base (1*b*).

Blackening, generally within 1 in. of ends (1*i*).

TABLE 21.—SUMMARY OF FLUORESCENT SERVICE SUGGESTIONS.—(*Continued*)

Blackening early in life (indicates active material from electrodes being sputtered off too rapidly) (2*a*, 2*b*, 3*a*, 3*b*, 5*a*, 6*a*).

Dark Streaks.—Streaks lengthwise of tube (1*j*).

Rings.—Brownish rings at one or both ends, about 2 in. from base (1*c*).

Dense Spots.—Black, about ½ in. wide, extending about half-way around tube, centering about 1 in. from base (3*d*).

*Ends Remain Lighted.**—(2*b*, 6*b*.)

*Blinking On and Off.**—Accompanied by shimmering effect during "lighted" period (1*a*).

Blinking of relatively new lamp (1*k*, 2*a*, 3*c*, 4*a*, 4*b*, 5*c*, 6*a*).

With two-lamp ballasts: if one lamp starts, one end of the other may blink on and off without starting; occasionally both lamps may start (6*c*).

No Starting Effort or Slow Starting.—(1*l*, 1*m*, 1*n*, 2*c*, 2*d*, 3*a*, 3*c*, 3*e*, 3*g*, 5*c*, 6*d*.)

Flicker (*Not Stroboscopic Effect*).—Pronounced, irregular flicker on looking directly at lamp (spiraling, swirling, snaking, etc.) (1*g*, 2*e*, 3*a*, 3*b*, 5*b*).

Flicker suddenly occurring (1*h*).

Persistent tendency to flicker (1*k*).

Dark Section of Tube.—One-third to one-half of tube gives little light (tubes longer than 24″) (6*e*).

Short Life.—(1*f*, 3*f*, 5*a*, 6*a*, 7*a*.)

Decreased Light Output.—(4*b*, 4*c*, 4*d*, 5*c*, 7*b*.)

During first 100 hr. use (1*d*).

Color and Brightness Differences.—Different color appearance in different locations of same installation (1*e*, 7*c*).

Lamps operate at unequal brilliancy (5*c*).

Noise.—Humming sound, which may be steady, or may come and go (3*h*, 3*l*).

Overheated Ballast.—(3*i*, 3*j*, 3*k*, 6*f*.)

Radio Interference.—(1*o*, 6*g*.)

Possible Causes†	Suggested Remedies
1. Lamps	
1*a*. Normal failure; active material on electrodes exhausted; voltage needed for operation exceeds voltage supply	Replace lamp (remove old lamp promptly)
1*b*. Normal—end of life	Replace lamp
1*c*. Likely a natural development during life, though improper starting may have some effect	New lamp, if appearance is too objectionable, or shield tube ends from view; check for proper starting

* Correct trouble at once, or remove lamp or starter, to avoid damage to lamp, starter, or ballast. Replacing starters with "No-Blink" types will help avoid future annoyance due to blinking.

† Service problems may arise from a combination of causes—not always from one single cause.

TABLE 21.—SUMMARY OF FLUORESCENT SERVICE SUGGESTIONS.—(*Continued*)

Possible Causes†	Suggested Remedies
1*d*. Light output during first 100 hr. is above published rating, sometimes as much as 10%. (Rating is based on output at end of 100 hr.)	
1*e*. Actual slight differences (in white or daylight lamps) may be discernible; perhaps wrong color lamp used; possibly lamp outside limits of color standards; or apparent color difference may be only difference in brightness between old and new lamp	Replace lamps if objectionable. (If warranted, color temperature can be checked in laboratory to determine whether there is a difference, and how much)
1*f*. Mortality laws (*i.e.*, for 2500-hr. average life, some will fail at shorter life, others last much longer than rated hours. 2500-hr. life based on operating lamp 3 to 4 hr. for each start)	
1*g*. New lamp may flicker	Flicker should clear up after lamp is operated or turned on and off a few times
1*h*. May suddenly develop in any lamp in normal service	Should clear up by itself
1*i*. Mercury deposit, common especially with 1-in. lamps	Should evaporate by itself as lamp is operated
1*j*. Globules of mercury on lower (cooler) part	Rotate tube 180 deg. Mercury may evaporate by increased warmth, though it may condense out again on cool side
1*k*. Possibly lamp at fault	Replace lamp. Investigate further if successive lamps blink or flicker in same lampholders
1*l*. Open circuit in electrodes, due to broken electrode, air leak, open weld, etc.	If open circuit is shown by test or inspection as in 3*g*, replace lamp
1*m*. Burned-out electrode (might be caused by placing one end of lamp across 115 volts)	If open circuit is shown by test or inspection as in 3*g*, replace lamp
1*n*. Air leak in lamp. In test with test lamp (see 3*g*), leak is indicated by absence of glow, though electrode lights up	Replace lamp

† Service problems may arise from a combination of causes—not always from one single cause.

TABLE 21.—SUMMARY OF FLUORESCENT SERVICE SUGGESTIONS.—(*Continued*)

Possible Causes†	Suggested Remedies
1*o*. Lamp radiation "broadcasts" through radio receiver	Locate aerial 9 ft. from lamp; or shield aerial lead-in wire, provide good ground, and keep aerial proper out of lamp and line radiation range
2. Starters	
2*a*. Starter defective, causing on-off blink or prolonged flashing at each start	Replace starter
2*b*. Ends of lamp remain lighted; starter failure due to:	
Short-circuited condenser in starter	Replace starter
Switch contacts welded together	Replace starter
2*c*. Starter at end of life	Replace starter
2*d*. Starter sluggish	Replace starter
2*e*. Starter not performing properly to preheat electrodes	Replace starter
3. Auxiliaries and Fixtures	
3*a*. No starting compensator in leading circuit of two-lamp ballast	Install compensator in series with starter in leading circuit. None required for 65- and 100-watt lamps
3*b*. Ballast improperly designed or outside specifications for lamp wattage, or wrong ballast being used	Use ETL approved ballasts of correct rating for lamp size
3*c*. Low ballast rating	Check ballast
3*d*. Normal—but if early in life indicates excessive starting or operating current	Check for ballast off-rating or unusually high circuit voltage
3*e*. Remote possibility of open-circuited ballast	Check ballast
3*f*. Improper ballast equipment on direct-current	Check ballast equipment
3*g*. Burned-out lamp electrodes due to	To determine necessity for replacing lamp, examine electrodes by viewing end of bulb against pinhole of light. (Or test by connecting base pins in series with test lamp on 115-volt circuit. Fluorescent glow means intact electrodes and active electrons)
Broken lampholders	
Lampholders with attached starter sockets, surface mounted on metal	
One strand of conductor touching grounded fixture	
Improper wiring	

† Service problems may arise from a combination of causes—not always from one single cause.

TABLE 21.—SUMMARY OF FLUORESCENT SERVICE SUGGESTIONS.—(*Continued*)

Possible Causes†	Suggested Remedies
	Correct
Direct-current operation without necessary additional resistance	Test Lamp Size: 60 watts; Fluorescent Lamp Size: 14 to 40 watts
Ground from some other cause	25 watts: Small diameter or miniature
	200 watts: 65 and 100 watts
3*h*. Slight transformer hum inherent in ballast equipment; varies in different ballasts. Objectionable amount may be due to improper installation or improper ballast design	Mount ballasts on soft rubber, Celotex, etc., to prevent transferring vibrations to supporting members, and to reduce hum to a minimum
3*i*. Short in ballast or capacitor	Replace ballast or capacitor
3*j*. High ambient temperature inside fixture housing	Refer to fixture manufacturer
3*k*. Prolonged blinking tends to heat ballast, and heating is aggravated under high ambient temperature inside fixture housing	See Blinking On and Off, and correct the cause
3*l*. Overheated ballast	See 3*i*, 3*j*, 3*k*, 6*f*
4. Temperature	
4*a*. Low temperature (difficulty may be experienced below 50°F.)‡	With thermal starter, can be operated at lower temperatures
4*b*. Cold drafts hitting tube	Enclose or protect lamp
4*c*. Where heat is confined around lamp, light output is lower	Better ventilation of fixture
4*d*. Low temperature operation. (Below 65° light loss is 1% or more per degree Fahrenheit)	Enclose
5. Voltage	
5*a*. Too low or too high voltage	Check voltage with range on ballast name plate
5*b*. High voltage starting	Check voltage
5*c*. Low circuit voltage. (Decreased ease of starting; also 1% change in light output for each 1% change in voltage, with output of "lagging"	Check voltage and correct if possible

† Service problems may arise from a combination of causes—not always from one single cause.

‡ For satisfactory starting and operation at low temperatures: (1) Keep line voltage up. (2) Conserve lamp heat (*e. g.*, by enclosure). (3) Use starters that provide higher induced starting voltages and longer electrode heating periods, *i.e.*, thermal switches.

TABLE 21.—SUMMARY OF FLUORESCENT SERVICE SUGGESTIONS.—(*Continued*)

Possible Causes†	Suggested Remedies
lamp—in two-lamp circuit—decreasing much faster than that of "leading" lamp)	
6. Circuit	
6*a*. Loose circuit contact (likely at lampholder) causing on-off blink	Lampholders rigidly mounted; lamp securely seated
6*b*. In new installation, circuit may be incorrectly wired	Check circuit wiring
6*c*. Individual starter leads from the two pairs of lampholders may be crisscrossed. (If this is the case, one lamp will not make starting effort unless the other is in its lampholders)	Rewire starter leads
6*d*. Possible open circuit	Test lamp in another circuit, being sure of proper contact in lampholders Check voltage from one lampholder to the other. (Use voltmeter or 220-volt 100-watt test lamp. Only one connection at each holder should be alive; hence four ways to check two live ones) If no voltage indication from lampholders, check circuit leads to lampholders If still no voltage, check circuit connection
6*e*. Direct-current operation without having and using reversing switches	Install reversing switches
6*f*. Short in wiring	Correct wiring
6*g*. Line radiation and line feedback	Apply line filter at lamp or fixture; sometimes possible to apply filters at power outlet or panel box
7. Operation	
7*a*. Too many lamp starts	Average life rating based on operating periods of 3 to 4 hr.
7*b*. Dust or dirt on lamp, fixture, walls, or ceiling	Clean
7*c*. May be due to reflector finish, wall finish, other near-by light, room decorations, etc.	Interchange lamps before assuming color difference

† Service problems may arise from a combination of cause—not always from one single cause.

CHAPTER VI

LUMINAIRE SELECTION

The Fundamental Concept of Lighting Quality.—The bulb size, shape, light diffusion, and distribution characteristics of fluorescent lamps introduced new considerations in lighting practice which called for new designs of reflecting and fixture equipment. In fact, the lighting industry and the public had become so accustomed to circular-shaped lighting equipment that early fluorescent luminaires were critically judged on their shape, degree of compactness, etc.[1] Although the elongated diffusing source with a tubular bulb precludes extreme accuracy of light control, still for most applications, well-designed reflecting equipments will be required to utilize most advantageously the light from fluorescent lamps. An advantage of the bulb size in many cases is that the reflector can be made of relatively small cross section to fit into restricted space. On the other hand, this is of advantage only where the lumen output is adequate for the application under consideration.

Although radically different types of reflecting equipment are required for fluorescent lamps, the fundamental principles of illumination remain unchanged. Our concept of practice as regards acceptable brightness, reflected glare, distribution of light, contrasts, and shadows must be given full consideration in the use of these new sources. Lighting specifications should adhere to established fundamentals and should not abandon any of the scientific facts upon which lighting practice has been advanced.

It is the purpose of this chapter to discuss the appraisal of fluorescent luminaires as regards their ability to provide comfortably the illumination levels represented by modern lighting

[1] Actually, the shape of fluorescent luminaires is more appropriate than circular fixtures, because most interiors are rectangular and have architectural features more dominantly linear. Certain fluorescent luminaires make possible efficient "lines of light" which have been wanted for years, especially by architects, for store and other commercial lighting applications.

practice. The "comfortable" qualification of course embraces all the ramifications of lighting quality.

The "efficiency" of a lighting system is sometimes expressed in terms of "so many footcandles per watt per square foot." As compared with filament lamps, fluorescent lamps give an excellent account of themselves when appraised on this basis. However, an installation should not be judged in such a narrow sense but rather by the all-round satisfactory character of the system. An installation that merely achieves specified foot-

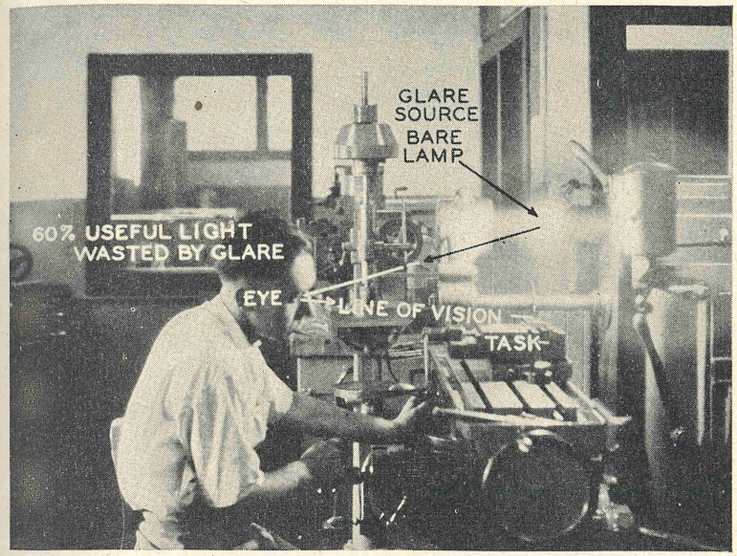


FIG. 74.—Glare interferes with seeing, cuts employee efficiency, and creates a potential accident hazard. As indicated by this illustration, 60 per cent of the useful light may be wasted where glare is present.

candle standards at the sacrifice of lighting comfort is seldom acceptable. In any event, almost all lighting installations represent a compromise between maximum utilization of the light produced by the source and maximum possible comfort conditions. Thus, intelligent engineering must be applied to avoid the inefficiency and waste that might result if systems were planned on the solitary basis of comfort.

Direct Glare.—Glare may be characterized as "light out of place," and its presence is the principal offender in producing uncomfortable lighting systems. Because glare actually inter-

feres with seeing, it reduces the effectiveness of the available footcandles (Fig. 74).

There are two types of glare, direct and reflected. Direct glare is the most frequent and serious cause of bad lighting, and it results, among other things, from unshaded or inadequately shaded light sources located within the field of vision, from too great a contrast between the bright light source and a dark background or from adjacent surfaces.

The effects of direct glare are well known to the lighting profession. For example, in merchandising interiors, glaring sources detract from the appearance of the room and divert attention from the articles on display. In industrial interiors, they make seeing more difficult and slow down production. In offices and schools, they lower visibility, cause eyestrain, and result in decreased accomplishment.

The question of whether unshielded fluorescent lamps are glaring in the various types of interiors has been much discussed ever since these lamps were introduced. The brightness of fluorescent lamps is very much lower than that of bare filament lamps of the wattage sizes commonly employed for general lighting—the maximum brightness of a 40-watt fluorescent lamp is even lower than the brightness of the 300- or 500-watt Glassteel Diffuser, which has found much favor in industrial lighting from the quality standpoint (Table 22). Nevertheless, certain standards of crosswise and lengthwise shielding of fluorescent lamps

TABLE 22.—BRIGHTNESS OF VARIOUS LAMPS AND LUMINAIRES

	Approximate Relative Brightness (40-watt White Fluorescent Lamp Taken as Unity)	
40-watt white fluorescent lamp	1	
200-watt inside frosted filament lamp (brightest spot)	37	
500-watt inside frosted filament lamp (brightest spot)	54	
200-watt filament lamp in 14-in. enclosing globe	0.90	
500-watt filament lamp in 18-in. enclosing globe	0.52	
300-watt Glassteel Diffuser	1.8 at 35°	1.5 at 70°
500-watt Glassteel Diffuser	3.1 at 35°	2.6 at 70°
Side of RLM reflector with two 40-watt fluorescent lamps	0.14	
30-watt white fluorescent lamp	1.35	
85-watt type RF lamp	2.6	
Maximum ceiling brightness using 500-watt silvered-bowl indirect luminaires	0.09	

have been followed by many progressive illuminating engineers. These standards are representative of modern fluorescent-lighting practice. For example, about 15 deg. of crosswise shielding is considered satisfactory for industrial lighting because (1) often the workmen are not "planted in one spot" (as is a draftsman, for example) and (2) good vertical illumination is needed—too much shielding reduces the light on vertical surfaces. However, in "lighting for seeing" areas (*i.e.*, in offices, schools, and the like), the appraisal is made on a somewhat different basis. In such interiors, the nature of the seeing task coupled with years of experience in providing optimum conditions of seeing comfort prompts the recommendation that fluorescent lamps have crosswise shielding within the normal field of view (usually considered up to 45 deg. above the horizontal) if most satisfactory and progressive fluorescent-lighting installations are to result. The visual task is usually less severe and more intermittent in stores, and shielding can be less.[1]

The rather common tendency of making bare-tube fluorescent-lamp installations when these lamps were first used, introduced in many cases an element of discomfort, distraction, and actual interference with seeing, often accompanied by less efficient utilization of the light itself. Although such installations may seem acceptable perhaps for store lighting or other locations where the seeing task is neither continual nor prolonged, it appears safe to predict that the most progressive and satisfactory installations will follow established shielding standards, regardless of the type of interior.

Reflected Glare.—Reflected glare comes from polished objects, such as encountered in machining metal parts, in the inspection of flat tinplate and other shiny surfaces, from glass-topped or varnished desks, or from glossy paper, paint, and the like. In short, any object whose reflection characteristics are predominantly specular can produce reflected glare by directing any high brightnesses which may exist into the eyes.

Reflected glare is also more objectionable than direct glare and quite frequently more harmful because it is generally from a direction below the horizontal, a zone in which the eye has no natural protection. Too, it is generally impossible to change the character of work or nature of the seeing task in order to

[1] See tabulation on p. 146.

avoid these potential reflections. Reflected glare may result from

1. The use of equipment that does not diffuse the light sufficiently to reduce its brightness when the reflected image is seen in the task.

2. The improper location of supplementary lighting equipment which permits bright reflections of the source to reach the eye.

Excessive reflected glare results in lower visibility, eyestrain, fatigue, loss of employee efficiency, and annoyance. Reflected glare is a much less important factor in stores than in factories, offices, schools, and similar locations where the visual tasks are often very critical and prolonged.

Maintenance.—An important factor in illumination design is that of maintenance, yet this factor is often neglected in selecting fluorescent luminaires. For no matter how carefully designed a lighting system may be with respect to the type of reflector, spacing of outlets, etc., good lighting will not be maintained unless the system is kept clean.

In general, maintenance involves keeping the lighting system at its maximum efficiency by replacing lamps and cleaning lamps and reflectors at periodic intervals. In operation, the illumination level gradually decreases because of (1) lamp light output depreciation, (2) the gradual accumulation of dust and dirt on lamps and reflecting surfaces, and (3) the gradual darkening of walls and ceilings. However, employees seldom are conscious of these gradual decreases in footcandle level because the decrease occurs at such a slow rate. A good installation may actually depreciate to less than half its initial value before it is realized that the lighting dollar is not producing "its dollar's worth of seeing light." It is therefore recommended that an illumination check be made with a footcandle meter periodically, say once every month, and when the footcandle level decreases to two-thirds of its 100-hr. value the lighting system should be cleaned. Such a procedure will determine an adequate cleaning schedule which can then be followed in the future. Of course, in addition to cleaning of the lighting units, the frequent painting and maintenance of the surroundings—side walls, ceiling, machinery, etc.—will help keep the lighting efficiency near the original value.

Cleaning the lighting equipment can best be accomplished by taking the luminaire down and washing it. Wiping out a

reflector with a damp cloth from a stepladder just pushes the dust "around from one corner to another." Using a dry cloth is worse for it not only fails to do a good cleaning job but also actually mars the reflecting surface by driving dirt and grime into it. Real washing will improve the illumination 10 to 15 per cent over the swabbing method. Alkaline solutions are satisfactory for porcelain enamel or glass surfaces but not for aluminum, because the alkali tends to attack the metal. Aluminum

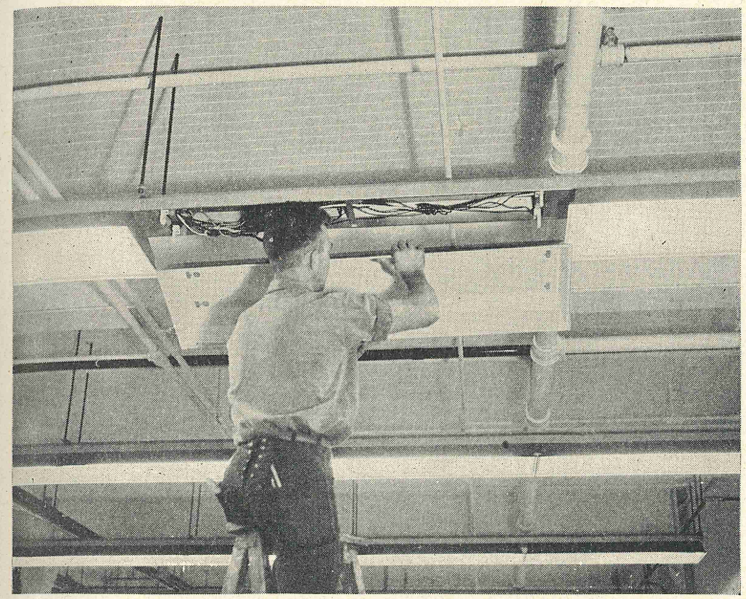


FIG. 75.—Many manufacturers are making their reflectors so they are quickly detachable. This promotes easy maintenance.

reflectors are best washed with wax or waxed emulsions or with neutral solvents.

Because of the importance of proper maintenance, many manufacturers of fluorescent industrial luminaires are making their reflectors quickly detachable (Fig. 75), so that they can be thoroughly washed on the floor (Fig. 76) without disturbing lampholders, starters, ballasts, or wiring. The task is also simplified by making the luminaires fairly accessible. Ordinary stepladders can be used for mounting heights up to about 12 ft.; two men and a special ladder will usually be required for mount-

ing heights above 20 ft. Industrial high-bay installations can sometimes be serviced from a crane. Disconnecting hangers can also be used. Figure 77 shows a two-lamp RF luminaire and a disconnecting hanger of the type now available. As much as 30 ft. of a continuous-row installation can be lowered for maintenance by such means, as shown in Fig. 78.

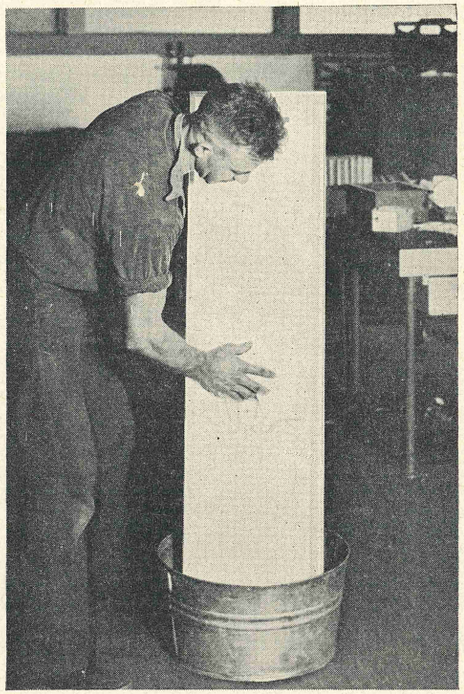


FIG. 76.—Adequate maintenance always means frequent thorough cleaning of reflectors. This is most effectively accomplished by washing them on the floor.

Generally speaking, it is important that dust collection on fluorescent luminaires be kept at a practical minimum from the standpoint of appearance and lighting economics. Therefore, units should be designed so as to be easily relamped and easily cleaned. This often-neglected consideration should enter every decision on the selection of fluorescent luminaires.

Illumination on the Horizontal Plane.—An illumination level of "so many footcandles" is commonly considered the illumination on the horizontal plane. Fluorescent luminaires should certainly be judged on their ability to put light efficiently down on the horizontal work surface, especially where they are to be used in offices where vertical illumination is of little concern. Luminaire appraisals from this standpoint are automatically included in cost of light calculations where the Coefficient of Utilization (in most cases, the efficiency of the system in producing horizontal footcandles) is a factor. It should be remembered that the output and type of distribution from a luminaire

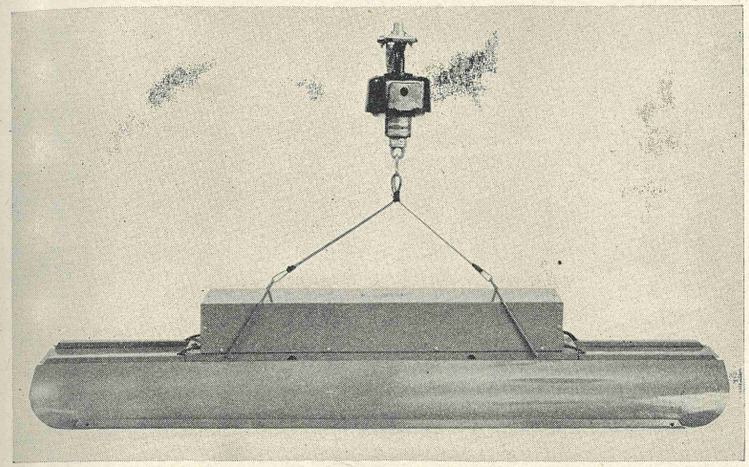


FIG. 77.—A cut-out hanger which facilitates the maintenance of lighting equipment located in inaccessible places.

determine the Coefficient of Utilization for a given room proportion and wall and ceiling reflectivities.

For example, a fluorescent fixture having an output of 75 per cent will produce 25 per cent more footcandles than a luminaire having a similar type of distribution but with only a 60 per cent output, all other conditions being equal. Thus, the customer can rightfully expect that luminaires having the type of distribution, appearance, etc., appropriate for his particular lighting task shall also have the highest possible output.

Illumination on Vertical Surfaces.—The selection of luminaires that provide an adequate amount of vertical illumination is particularly important in the store and in the factory. Its importance in store lighting results from the fact that a goodly

proportion of the merchandise is displayed in wall cases or on shelves, and the footcandle level on the vertical surface must make labels, colors, etc., quickly and easily apparent. Vertical illumination is important in the factory because of the many vertical-plane seeing tasks, such as gages and verniers on machines, etc. In fact, the illumination on the vertical surface may often be fully as important in industrial lighting as illumination on the horizontal plane.

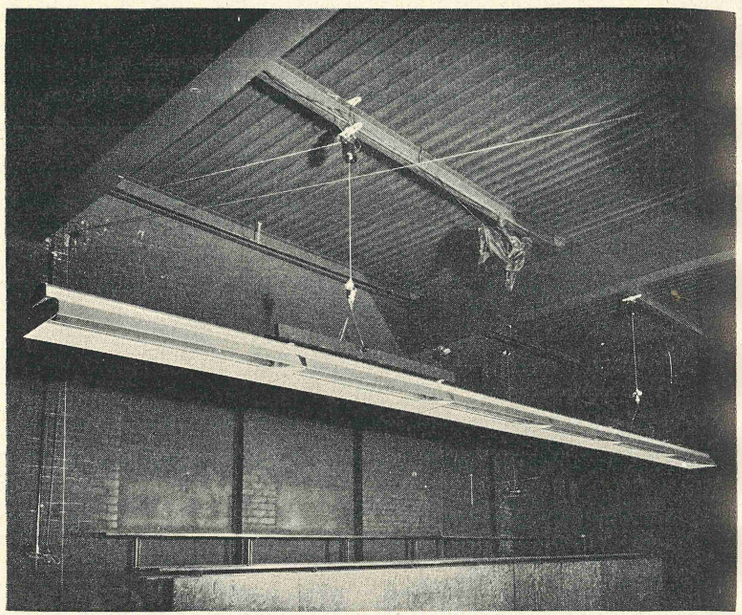


FIG. 78.—Continuous-row installations of fluorescent equipment can also be lowered by disconnecting hangers.

Appearance of the Lighted Room.—Although the appraisal of fluorescent fixtures in terms of the resultant appearance of the lighted room unquestionably enters the selection of equipment, appearance is not a criterion of a luminaire's value from the standpoint of good seeing conditions or freedom from eye fatigue. Frequently, compromises with the utilization of light are made in the design of fluorescent luminaires for use in commercial interiors. However, advances in the fixture art have resulted in a wide variety of luminaires suitable from the standpoint of both

appearance and lighting efficiency for commercial interiors. Many customers have expressed a preference for troffer systems in offices and stores because of their relatively high utilization, their cost advantages, and their pleasing appearance. Generally speaking, recessed and ceiling-mounted equipments receive much present customer favor.

Candlepower-distribution Curves.—The candlepower-distribution curve is the graphic description of a luminaire's performance. It is to the lighting man what a name-plate rating on an electric motor is to the electrical engineer. The ability to evaluate the appropriateness of a fluorescent fixture for a particular seeing task simply by studying its distribution curve is an essential requirement for any engineer who would choose

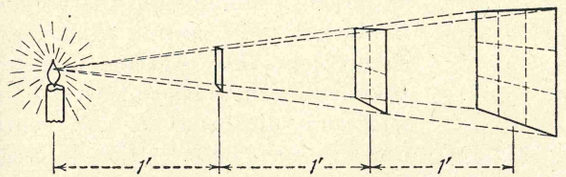


FIG. 79.—The graphic explanation of the inverse-square law. It is obvious that the plane 2 ft. away from the light source spreads the same amount of light over four times the area of the plane at 1 ft. The footcandle level at 2 ft. will therefore be one-fourth that at 1 ft. At 3 ft. it will be one-ninth, etc.

luminaires most wisely. As a necessary background for interpreting and using distribution curves, it will first help to understand how they are obtained.

Because candlepower-distribution curves and the methods of obtaining them can be more easily explained for nearly point sources, some of the fundamental concepts that follow will be discussed and illustrated in terms of well-known filament luminaires.[1] This explanation will be followed by a discussion of the differences betwen filament- and fluorescent-lamp distribution curves and the methods by which they are obtained.

The candlepower in any direction from a lighting unit is equal to the footcandles produced on a plane at right angles to the light rays multiplied by the square of the distance in feet from the luminaire to the point of measurement. This is simply an application of the inverse square law which indicates that the illumination produced by a small light source decreases in

[1] R. F. CISSELL, "Distribution Curves," *Magazine of Light*, No. 1, 1940.

proportion to the square of the distance from the source. The reason is pictured in Fig. 79 in which the standard candle produces (by definition) 1 footcandle on the first plane, 1 ft. away. If this plane is removed 1 ft., the same amount of light would be spread over four times the area and the average density of light would be but one-fourth as great, or ¼ footcandle. By the same token, the illumination level would be ⅑ footcandle at 3 ft., or 1/100 footcandle at 10 ft.

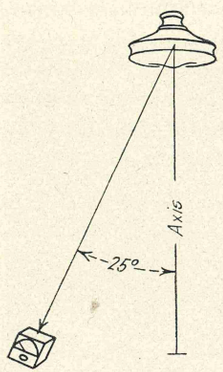


FIG. 80.—The inverse-square law can be used in determining the candlepower emitted by a luminaire in a particular direction. In this case the meter is 10 ft. from the light source and reads 4 footcandles. Candlepower = $4 \times 10^2 = 400$.

Suppose for example that a 48-in. fluorescent lamp were used in Fig. 79 instead of a candle. Light could then go around the first plane and still strike the second. Thus as the light source increases in size, the variation in illumination (particularly near the source) will deviate from the inverse square law. For accurate measurements, the distance should be at least five times the maximum dimension of the source; ten times is even better. For fluorescent fixtures using 4-ft. 40-watt lamps, the inverse square law should not be applied at distances less than 20 ft. from the fixture. The candlepower for a luminaire can be determined in this way at any angle from the vertical, say at 25 deg. as in Fig. 80. The reason why the measurement should be made at right angles to the light ray is shown in Fig. 81. If measurements are made in a tilted rather than a perpendicular plane, the same amount of light would be spread on a greater area[1] and the measurement would be less.

For a symmetrical type of luminaire (and most filament-lamp luminaires employed for general lighting are symmetrical), the candlepower measurement of Fig. 80 at 25 deg. would be the same for all 25-deg. angles around the vertical axis. This is illustrated in Fig. 82. In such cases, the first measurement gives

[1] In Fig. 80, the area of plane B is equal to $\frac{\text{area of plane } A}{\text{cosine of angle } X}$, where X is the tilting angle. If planes A and B were equidistant from the source, the footcandles at B would then equal the footcandles at A times the cosine of X.

all the necessary information about the candlepower value at 25 deg., and it is easy to visualize the same value of candlepower all around the axis. Actually, in laboratory photometric work involving symmetrical types of filament luminaires, any slight differences that might be present because of filament structure or variations in the luminaire are compensated for by rotating the unit. One reading then is known to represent the average candlepower value at that angle.

To get the complete candlepower-distribution curve for the fixture, the inverse square law is used to determine the candlepower at other angles from the vertical just as it was done at 25 deg. in Fig. 80. The value at 90 deg., for example, gives the

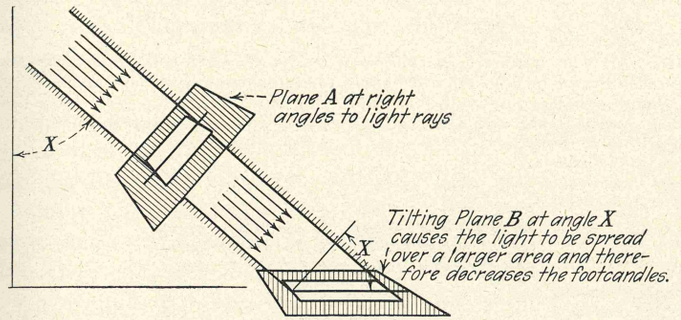


FIG. 81.—When the plane of measurement is tilted at some angle to the light rays producing the illumination, the light is spread over a greater area and the footcandle level on the tilted plane will be reduced.

candlepower straight out horizontally from the unit whereas that at 0 deg. is directly below. When these data are plotted on polar coordinate paper, the familiar candlepower-distribution curve of the unit is obtained (Fig. 83).

The essential difference in photometric measurements on fluorescent-lamp fixtures is that the units are not symmetrical and therefore candlepower measurements in one plane do not represent the average candlepower in all vertical planes. Candlepower measurements in a vertical plane through the center of the luminaire and at right angles to the lamps will give one distribution curve. Measurements in a vertical plane through the center of luminaires parallel with the lamps will give another curve. Measurements in any vertical plane through the center of the fixture at any angle in this 90-deg. range between normal to

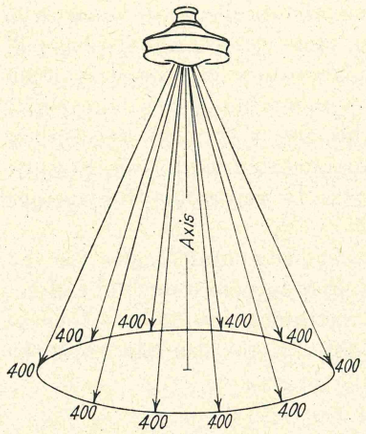


FIG. 82.—The symmetrical type of luminaire shown in Fig. 80 will have the same candlepower value at all 25-deg. positions (or any other given angle) around the axis.

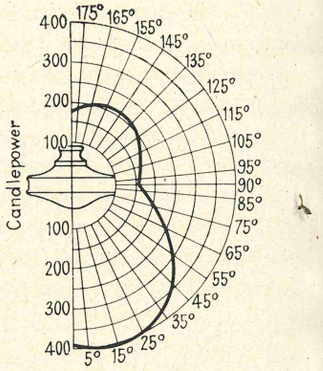


FIG. 83.—The complete candlepower distribution curve is obtained by plotting the values on polar coordinate paper and connecting the points with a smooth curve.

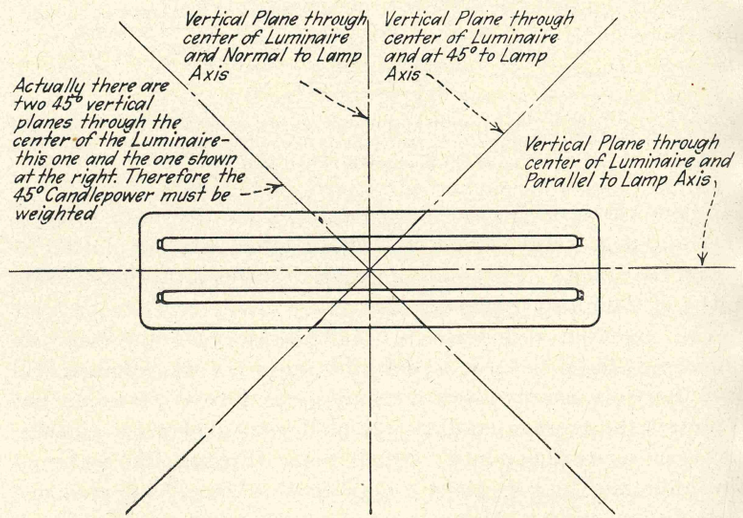


FIG. 84.—The three planes of measurement commonly shown for fluorescent luminaires.

the lamps and parallel to the lamps will also give a different distribution curve. Theoretically, measurements would have to be made in an infinite number of planes to determine the average candlepower. Actually, most photometric reports on fluorescent luminaires show measurements in three vertical planes: (1) normal to the lamp axis, (2) parallel to the lamp axis, and (3) at 45 deg. to the lamp axis. In many cases, measurements (though not indicated) are also taken at 22½ and 67½ deg. to the lamp axis. Greater accuracy in calculating the average candlepower curve will be secured if measurements are made in five planes, but average values based on the three planes normally shown are sufficiently close for all but the most precise illumination calculations. These three planes are shown in Fig. 84. The candlepower measurements in the 45-deg. plane must be weighted twice because there are two 45-deg. planes in the complete 360 deg. around the fixture and but one plane normal to the lamp axis and but one plane parallel to the lamp axis. For example, if a certain fluorescent fixture had values of 1310, 1210, and 1250 candlepower at 25 deg. in the normal, parallel, and diagonal planes, respectively, the average candlepower would be

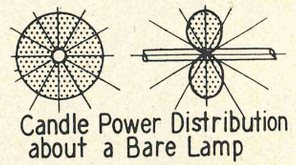


FIG. 85.—The crosswise (left) and lengthwise (right) distribution curves of a bare fluorescent lamp.

$$\frac{1310 + 1210 + (2)(1250)}{4} = 1255 \text{ candlepower}$$

The difference between the crosswise and the lengthwise distribution of light from fluorescent fixtures results chiefly from the fact that the fluorescent lamp has a different distribution normal to the axis of the lamp then in the plane of the axis as shown in Fig. 85. The actual variation between candlepower-distribution curves measured in normal, parallel, and diagonal planes is also influenced by the design of the luminaire. Figure 86 shows curves on a fixture whose distribution in the three planes are quite similar. Figure 87 shows the curves on another unit where the distributions differ widely. The weighted-plane method described above results in more accurate average candlepower values if the distributions in the planes of measurement are not widely different.

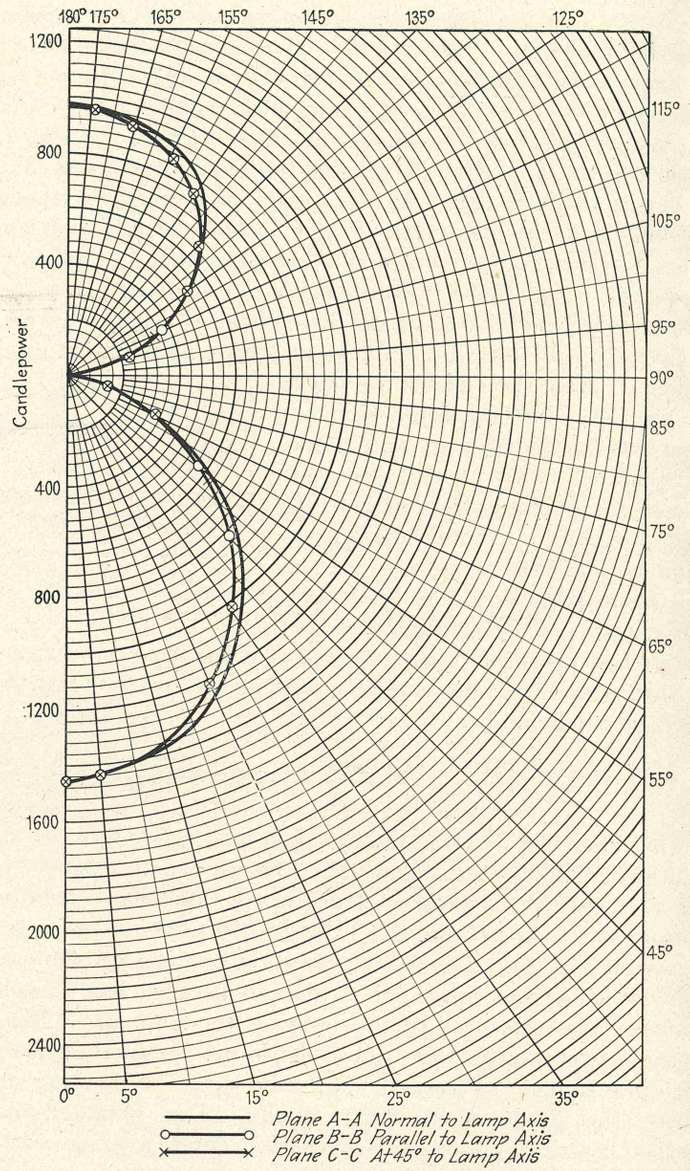


FIG. 86.—Distribution curves of a typical fluorescent luminaire in which candlepower values in the three planes are quite similar.

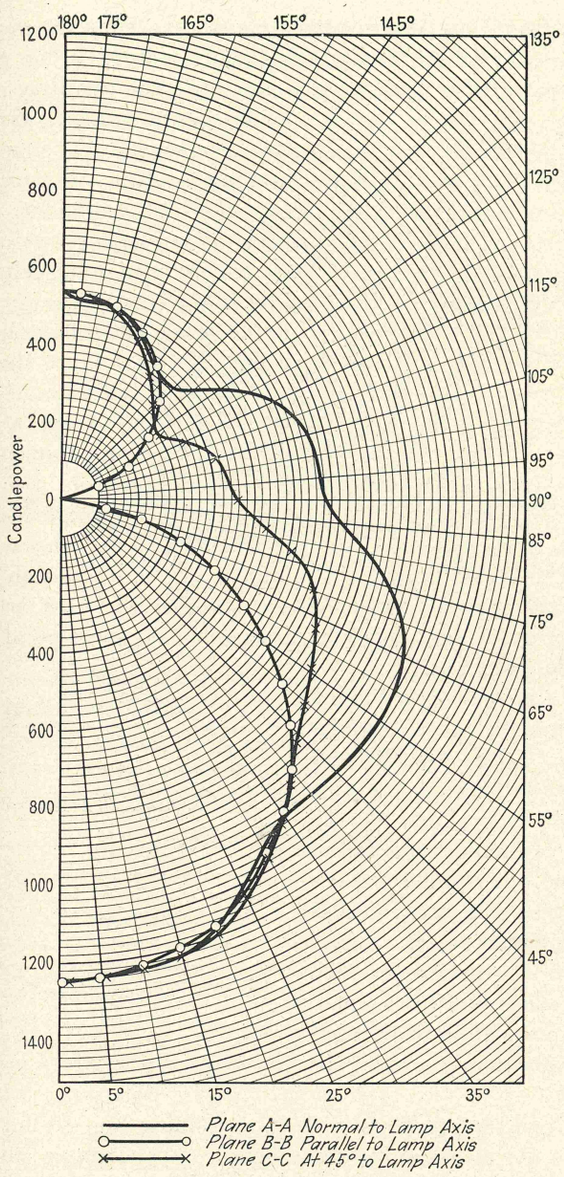


FIG. 87.—Candlepower distribution curves of a fluorescent luminaire in which values in the three planes vary considerably.

Going from Candlepower to Lumens.—Perhaps the most puzzling part of the candlepower-distribution story is the problem of determining the number of lumens, *i.e.*, the quantity of light, which result from a given distribution curve. The method of making such a transformation can be best explained on the basis of a very simple case, a source having a uniform luminous intensity of 1 candlepower located in the center of a sphere having a radius of 1 ft. Since the lumen is defined as the amount of light that is intercepted by a surface of 1 sq. ft., every point of which is 1 ft. away from the source having a uniform intensity of 1 candlepower, we know that 1 lumen will fall on each square foot of the sphere's inner surface whether the area is square, round, irregular, or a ring around the sphere at some point. This is illustrated in Fig. 88.

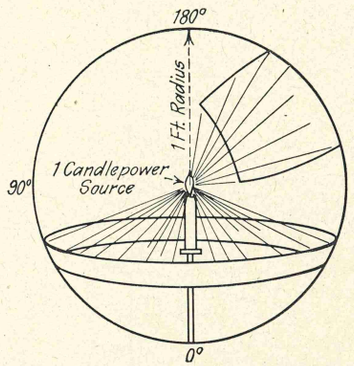


FIG. 88.—The fundamental concept of going from candlepower to lumens. If both square and ring have areas of one square foot, each will intercept one lumen.

If the sphere is then divided into bands or zones (usually eighteen 10-deg. zones from 0 deg. directly beneath the unit to 180 directly above it), the number of lumens that fall in each zone will equal 1 candlepower times the area of that zone in square feet. Figure 89 shows the sphere divided into 18 zones of 10 deg. each. These zones should be thought of as rings running around the sphere.

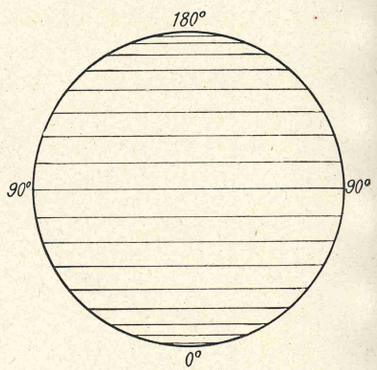


FIG. 89.—The eighteen 10-deg. zones commonly used in general photometric work.

The important point to note in examining Fig. 89 is that the zones do not all have the same areas. For example, the zones near the horizontal axis are much larger in area than the zones near the vertical axis. This difference in area can be illustrated

by assuming that the sphere is covered with some material so that the individual zones can be peeled off and laid out flat as shown in Fig. 90. The difference is then quite apparent. For another illustration of the decrease in size of the zone from the center to the top and bottom, assume that two men agree to paint the hemispherical dome of a building in a series of 10-deg. horizontal stripes and they decide to paint the same number of stripes each. If one started at the top, the other at the bottom, it may be readily seen (Fig. 91) that the amount of work done by the man at 180 deg. would be considerably less than by the man

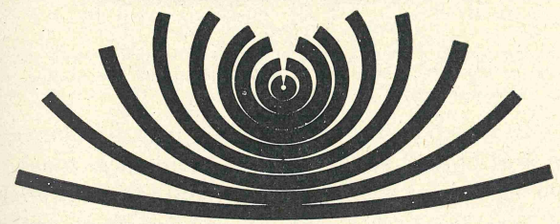


FIG. 90.—The area (and thus the light intercepted) of the various zones are quite different. Here the nine 10-deg. zones from 90 to 180° are laid out flat to show their relative areas.

at 90 deg. Similarly, a given candlepower in a zone near the vertical means much less lumens than the same candlepower in a zone near the horizontal.

The area of each of these zones in the 1-ft. radius sphere can also be determined mathematically.[1] These areas are called zonal constants and are given to the nearest 0.01 in Table 23.

TABLE 23.—ZONAL CONSTANTS

Zone, Degrees	Constant
0–10 and 170–180	0.10
10–20 and 160–170	0.28
20–30 and 150–160	0.46
30–40 and 140–150	0.63
40–50 and 130–140	0.77
50–60 and 120–130	0.90
60–70 and 110–120	0.99
70–80 and 100–110	1.06
80–90 and 90–100	1.09

[1] The zonal constant for any zone $A - B = 2\pi(\cos A - \cos B)$. For example, the constant for the

30- to 40-deg. zone $= 2\pi(\cos 30° - \cos 40°)$

$= (6.28)(0.866 - 0.766) = (6.28)(0.10) = 0.63.$

With a 1-candlepower source at the center of a sphere 1 ft. in radius, 1 lumen falls on each square foot. The lumens in each zone is simply equal to the area of that zone in square feet. Thus

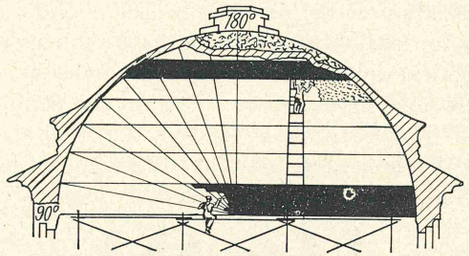


FIG. 91.—A common place illustration of the difference in area of the various zones shown in Fig. 89. Painting a 10-deg. stripe at the 90-deg. position is 11 times as much work as at the 180-deg. position.

there is 0.10 lumen in the zone directly over the source because it has an area of 0.10 sq. ft. (the 170- to 180-deg. zone). In the 90- to 100-deg. zone which is a ring of relatively large area around the source, there will be 1.09 lumens, for that zone has an area of 1.09 sq. ft. If we replace the 1-candlepower source with one of 10 candlepower, the lumens in each zone will simply equal the zonal constant times 10.

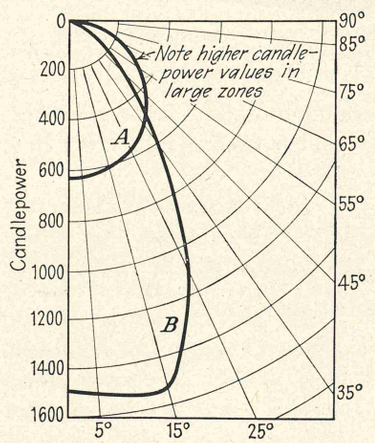


FIG. 92.—A point to remember—the area enclosed by a candlepower distribution curve is not a criterion of luminaire's output. The total lumens are the same for each of the two curves shown here.

These zonal constants can also be applied to practical distribution curves with candlepowers varying at the different angles. By dividing the distribution curves of actual sources into eighteen 10-deg. zones just as was done above, it can be assumed that the candlepower value at the center of each zone represents the average candlepower over the entire zone. To get the lumens in the 0- to 10-deg. zone, simply multiply the candlepower at 5 deg. by 0.10, the zonal constant for that zone. Likewise, the lumens in the 80- to 90-deg. zone would be equal to the

candlepower at 85 deg. times 1.09, the constant for the big zones on either side of the horizontal. Table 24 shows the computations of lumens for the filament-lamp candlepower-distribution curve shown in Fig. 83. Note that in the 50- to 60-deg. zone, for example, there are 270 lumens with a mean candlepower of 300, whereas 400 candlepower in the 0- to 10-deg. zone produce only 40 lumens.

TABLE 24.—COMPUTATION OF LUMENS FROM CANDLEPOWER VALUES OF FIG. 83

Angle, degrees	Candlepower	Zone, degrees	Zonal constant (Table 23)	Zonal lumens
0	390			
5	400	0–10	0.10	40
15	410	10–20	0.28	115
25	400	20–30	0.46	184
35	380	30–40	0.63	239
45	340	40–50	0.77	262
55	300	50–60	0.90	270
65	250	60–70	0.99	248
75	200	70–80	1.06	212
85	175	80–90	1.09	191
90	165			
95	165	90–100	1.09	180
105	170	100–110	1.06	180
115	185	110–120	0.99	183
125	200	120–130	0.90	180
135	205	130–140	0.77	158
145	210	140–150	0.63	132
155	205	150–160	0.46	94
165	200	160–170	0.28	56
175	195	170–180	0.10	20
				2942

On the assumption that a 200-watt lamp (3700 lumens) was employed, the luminaire efficiency would be 2942/3700 = 79.5 per cent.

This method is applied in an identical manner to fluorescent luminaires. If the average candlepower values as determined by the proper weighting of candlepower measurements in the various planes are multiplied by the appropriate zonal constants, the lumens in each zone can be determined. Table 25 shows this tabulation for the fluorescent luminaire whose distribution curve was shown in Fig. 86.

TABLE 25.—COMPUTATION OF LUMENS FROM CANDLEPOWER VALUES OF FIG. 86

Angle, degrees	Candlepower			Weighted average candlepower	Zone, degrees	Zonal constant	Zonal lumens
	Plane *AA**	Plane *BB*†	Plane *CC*‡				
0	1460	1460	1460	1460			
5	1450	1440	1450	1448	0 –10°	0.10	145
15	1390	1360	1360	1368	10°–20°	0.28	383
25	1280	1210	1230	1237	20°–30°	0.46	569
35	1100	1020	1040	1050	30°–40°	0.63	660
45	885	805	820	833	40°–50°	0.77	641
55	630	575	575	589	50°–60°	0.90	530
65	355	337	338	342	60°–70°	0.99	338
75	178	144	155	158	70°–80°	1.06	168
85	93	40	73	70	80°–90°	1.09	76
90	97	0	68	58.2			
95	139	45	112	102	90°–100°	1.09	111
105	249	209	220	225	100°–110°	1.06	238
115	368	371	346	358	110°–120°	0.99	354
125	491	520	505	505	120°–130°	0.90	455
135	645	655	680	665	130°–140°	0.77	512
145	835	780	800	804	140°–150°	0.63	506
155	915	870	850	871	150°–160°	0.46	401
165	940	935	895	916	160°–170°	0.28	256
175	970	965	955	961	170–°180°	0.10	96
							6439

Luminaire had four 40-watt white fluorescent lamps, each having an output of 2100 lumens.

$$\text{Luminaire efficiency} = \frac{6439}{(4)(2100)} = \frac{6439}{8400} = 77 \text{ per cent}$$

* In this test, plane *AA* was normal to the lamp axis.
† In this test, plane *BB* was parallel to the lamp axis.
‡ In this test, plane *CC* was 45 deg. to the lamp axis.

It should be remembered that the area enclosed within a candlepower-distribution curve is not a criterion of a luminaire's output. Figure 93 shows curves for two units that emit the same amount of light, although the areas enclosed within the two curves are very different. The effect of the large zones near the horizontal which are rich in lumens may be seen in curve *A*, and, although curve *B* provides more light directly under the unit, the higher candlepower values are in those small zones near the vertical and they account for relatively few lumens.

Once the interpretation of the candlepower-distribution curve is mastered, it becomes a valuable tool to the lighting man in appraising the performance of a luminaire and in determining its appropriateness for a particular lighting application. It should be remembered, however, that candlepower-distribution curves of fluorescent luminaires cannot be used with the inverse square

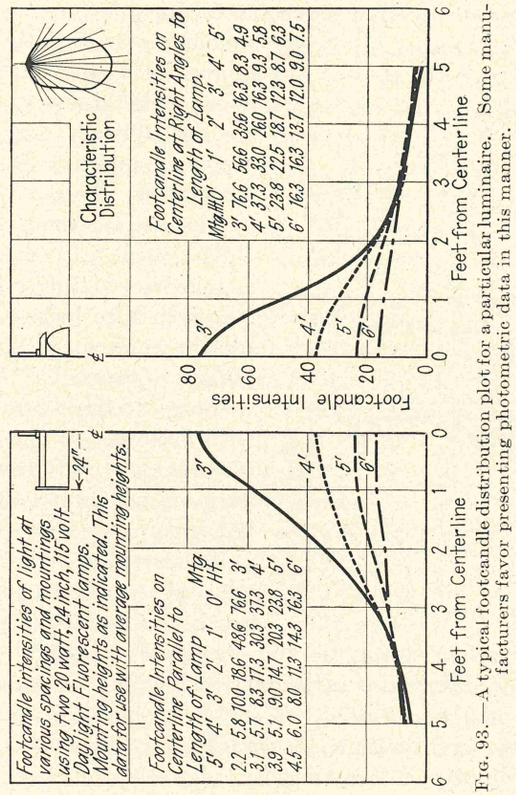
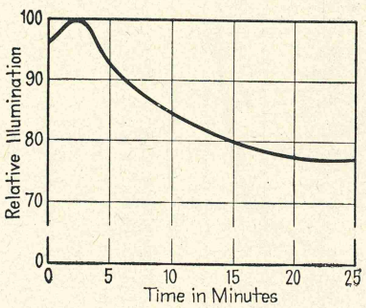


FIG. 93.—A typical footcandle distribution plot for a particular luminaire. Some manufacturers favor presenting photometric data in this manner.

law to determine footcandle levels at particular distances unless those distances are at least five times the maximum dimensions of the fluorescent luminaire. To eliminate any chance of making such a mistake, some manufacturers have shown footcandle plots in their catalogues for various fixtures and mounting heights. Such a method of presentation is shown in Fig. 93.

How Light Output Available Affects Luminaire Design.—The introduction of fluorescent lamps in low-wattage units with relatively low lumen outputs per foot no doubt brought some confusion. A decade of general lighting practice led to the common use of lamps that delivered 5000, 10,000, 20,000 and, in the case of 1500-watt lamps, 33,000 lumens from a single source. Obviously, lighting technicians were scarcely prepared to revert to low-powered sources and logically were at some loss to comprehend both the economics and the methods by which large groups of 15-, 20-, 30-, or 40-watt lamps might replace in practice the 500- or 1,000-watt lamps then commonly used for general lighting.



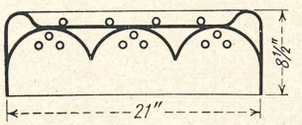


Fig. 94.—The output of a fixture is reduced if proper consideration has not been given for ventilation in the design. In the case illustrated the reduction was 22 per cent.

The result, of course, is that a relatively large number of lamps have to be used in fluorescent luminaires to secure the higher footcandle standards without "filling" the interior with fixtures. Because fluorescent lamps of different wattage sizes are not interchangeable in the same sockets, the designer of fluorescent installations must not only consider normal depreciation in light (by allowing for depreciation down to the designed average footcandle level in service) but also anticipate the illumination requirements for the normal life of the system either by providing an abundant footcandle level initially or by planning for the addition of other lamps or complete fixtures later.

Luminaire Temperature Considerations.—It was explained in Chap. III that the light output and the performance of fluorescent lamps varies with the surrounding or ambient temperature, the rated light output being obtained at ambient temperatures of 70 to 80°F. For this reason, consideration must be given to operating temperatures in the design of fluorescent equipment, and, if those temperatures exceed the recommended ranges,

adequate provision should be made for heat dissipation. Some cautions and ventilation hints are given in Chap. III.

For example, tests made on a dusttight industrial unit using two 40-watt daylight fluorescent lamps showed that a 10 per cent decrease in light output resulted because of the increased ambient temperature around the lamps. Of course, absorption by the cover glass of such units will cause a further reduction, the amount depending on the glass used. An even more extreme case is shown in Fig. 94. As indicated by the cross-sectional view, the unit had an open bottom and in each of the small reflector sections were located three 30-watt fluorescent lamps. After the luminaire was operated for 25 min., the illumination decreased 22 per cent, the result of the gradual rise of the ambient temperature around the lamps to 174°F. (the normal room temperature was 70 to 80°F.).

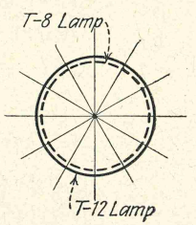


Fig. 95.—Crosswise distribution curves of the 30-watt T-8 fluorescent lamp and the 40-watt T-12 lamp referred to in several of the illustrations that follow. For comparison the curve of the bare T-12 lamp is repeated on each web.

Further tests with fixtures having more typical loadings prove that the loss in light output due to operating temperature is quite small in well-designed luminaires and with normal room ventilation.

Excessive temperatures within the fixture can also harm the auxiliary equipment. As has been mentioned, particular care must be given to the sound-deadening material on which ballasts are sometimes mounted to make certain that such materials do not prevent proper dissipation of the ballast heat.

Controlling the Light from Fluorescent Lamps.—The field of light control embraces the subjects of reflector contour, reflector finish, reflector size, characteristics of transmitting materials, and lenses. In the case of the fluorescent lamp, in which the source is in the form of a long cylinder, reflectors and lenses can provide effective directional control of light only in planes crosswise of the lamp, *i.e.*, the planes at 90 deg. to the lamp axis. Much work has been done to show how the various control factors affect the crosswise distribution of fluorescent equipment. Notable among the workers in this field are Potter and Darley.[1]

[1] W. M. Potter and W. G. Darley, "The Design of Luminaires for

Figure 95 shows the relative candlepower-distribution curves for the bare 30- and 40-watt lamps used in their tests. Although these are relative candlepower plots, the difference between the two curves indicates that the 40-watt T-12 lamp is more efficient than the 30-watt T-8 lamp (see Table 4).

The Effect of the Specular-reflector Contour.—Figure 96

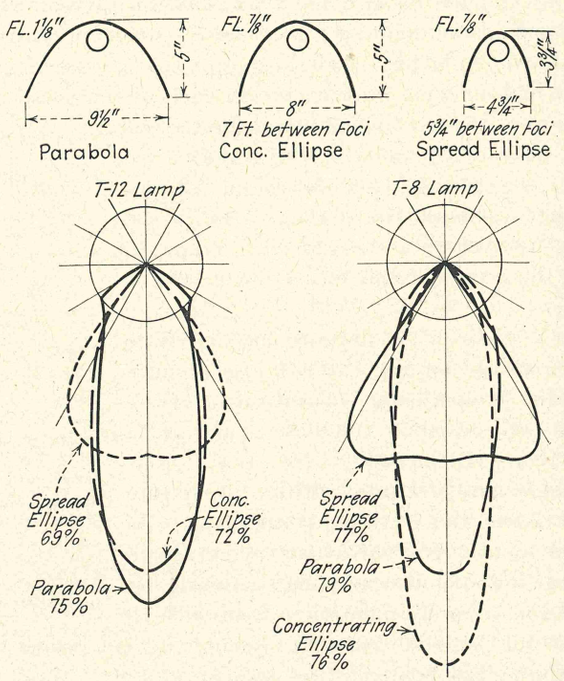


FIG. 96.—The contour of specular reflectors greatly influences the crosswise distribution from fluorescent troughs.

shows the crosswise distribution from specular reflectors having three different contours—parabolic, concentrating ellipse, and spread ellipse. The letters FL stand for focal length. Notice that the output is greater with the 30-watt T-8 lamp in all three contours because of the smaller source diameter. Also, the downward candlepower of the 30-watt T-8 lamp in the concentrating ellipse reflector shown is actually greater than in the case of the 40-watt T-12 lamp in the same contour. In this case, the smaller source diameter more than makes up for the less available light.

Fluorescent Lamps," *Illuminating Engineering*, November, 1940. (Several of the illustrations in this chapter were originally published in that I.E.S. paper.)

Of course, this effect is of considerable importance for those applications where the amount of light down on the working plane is of more concern than the efficiency of the reflecting equipment.

Effect of Reflector Depth.—Figure 97 shows the cross section and crosswise distribution curves for a specular parabolic trough of three depths. Note that, although the element efficiency is reduced as the depth is increased, the maximum candlepower actually increases as much as 25 per cent in going from 3 to 5 in. of depth, the focal length being the same and the lamp remaining at focus. Additional increases in depth give a smaller gain in maximum beam candlepower but with large increases in the reflector volume.

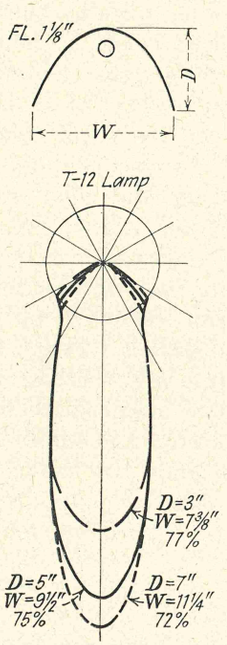


FIG. 97.—The effect of depth on a specular parabolic trough reflector.

Although the shape of the crosswise distribution curves changes little with the different depths, the degree of shielding is, of course, affected. The cut-off (and the shielding) will be less at smaller depths, though such units are more efficient because less reflecting surface is presented to direct the light and thus less is lost by absorption.

Reflector Finishes.—If a surface is so rough that it has absolutely no sheen, a beam of light striking it will be reflected in all directions. A piece of white blotting paper, for example, when placed in the path of a beam of light, will be equally bright when viewed from any angle. Even when the angle is such that the surface is apparently only half as wide (foreshortened viewing), the surface looks just as bright as though it were at right angles to the line of vision with twice as much area visible. This is called "diffuse reflection."

Since light that falls upon a rough or mat surface is reflected in all directions, it follows that the shape of reflectors with such a surface can have but little effect on the resulting distribution of light. In Fig. 98, *S* represents a light source at the mouth of a rough-surface reflector *aaa*. The light distribution is the same when the reflector has the cross section *aaa*, *bbb*, or *ccc*, for when the reflector is viewed from below, it simply appears as a white disk. However, if a contour such as *bbb* or *ccc* is used rather than *aaa*, there will result a needless absorption of light due to cross reflection. Thus the light from the source is better utilized with the shape *aaa*.

This classic example has been used for years to describe the lack of control exhibited by certain reflecting materials. Figure 99 illustrates diffuse and specular reflection and the two intermediate steps of spread reflection and diffuse-specular reflection. Figure 100 shows how the various reflecting materials are classified with respect to these four divisions.

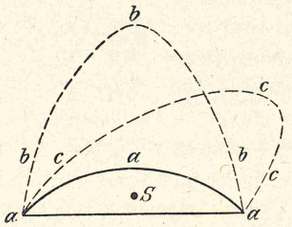


FIG. 98.—The shape of a rough-surface reflector (diffuse material) has relatively little effect on the distribution.

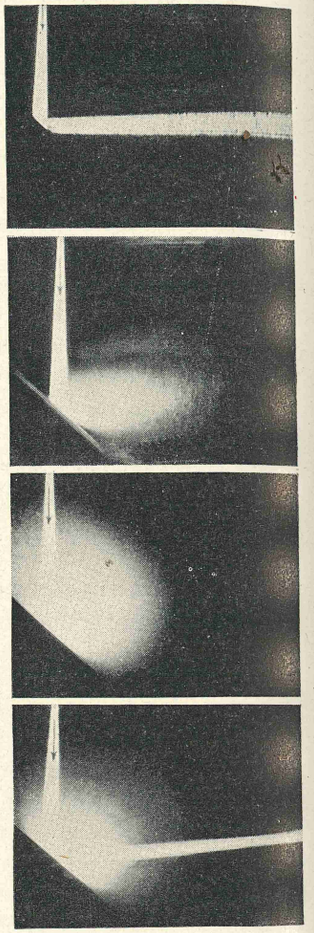


FIG. 99.—The four types of reflection. From top to bottom: specular, spread, diffuse, and diffuse specular.

Specular reflecting materials must be employed where accurate control is necessary. Generally speaking, the smooth surface of specular reflectors makes them easy to clean, although some

materials, such as polished silver, must be protected from the atmosphere whereas others can be used exposed without serious depreciation. Plane-specular or mirrored surfaces appear dark except when the eye is in the path of the beam, at which position the reflected image is only slightly less bright than the source.

Quite the opposite is diffuse reflection where there is no directional control but light is reflected at all angles. Such materials are used wherever good diffusion of light is desired as for ceilings, walls, and architectural element cavity finishes. The maintenance characteristics of diffusing materials are however, inferior to specular surfaces, for the dust collects more rapidly in the various pits and depressions and makes cleaning more difficult. Diffuse reflection surfaces have no bright spots, rather a surface that appears almost equally bright from all angles of view.

The diffuse-specular surface, is, in effect, a diffuse surface with a shiny transparent finish, similar to plate glass over blotting paper. Such surfaces give no directional control except for the specularly reflected rays which usually amount to only 5 to 15 per cent of the incident light. Glossy porcelain enamel of the type commonly used in fluorescent-lighting equipment is a good example of this type of reflection. Diffuse-specular surfaces produce a bright image of the light source on a luminous background of diffused light, so such finishes would be undesirable for walls and ceilings. Diffuse-specular surfaces are easy to clean, and the glazed finish results in permanency of the reflecting surface.

Spread reflection is obtained with unpolished metals and similar surfaces that direct light with less concentration than polished surfaces, *i.e.*, individual rays are reflected at slightly different angles but all in the same general direction. There is partial diffusion of the light. Materials having such characteristics are used for reflectors that require a smooth beam and moderate light control, their maintenance being inferior to specular surfaces because they collect dust and dirt more rapidly. Spread-reflection surfaces spread the light so that the source is not definitely mirrored, but since the diffusion is incomplete, the surface brightness is definitely related to the viewing angle. For example, aluminum-painted surfaces appear bright at certain viewing angles and dark at others.

Figure 101 shows the effect of these four different types of finishes on a parabolic contour. Of course, the greatest control

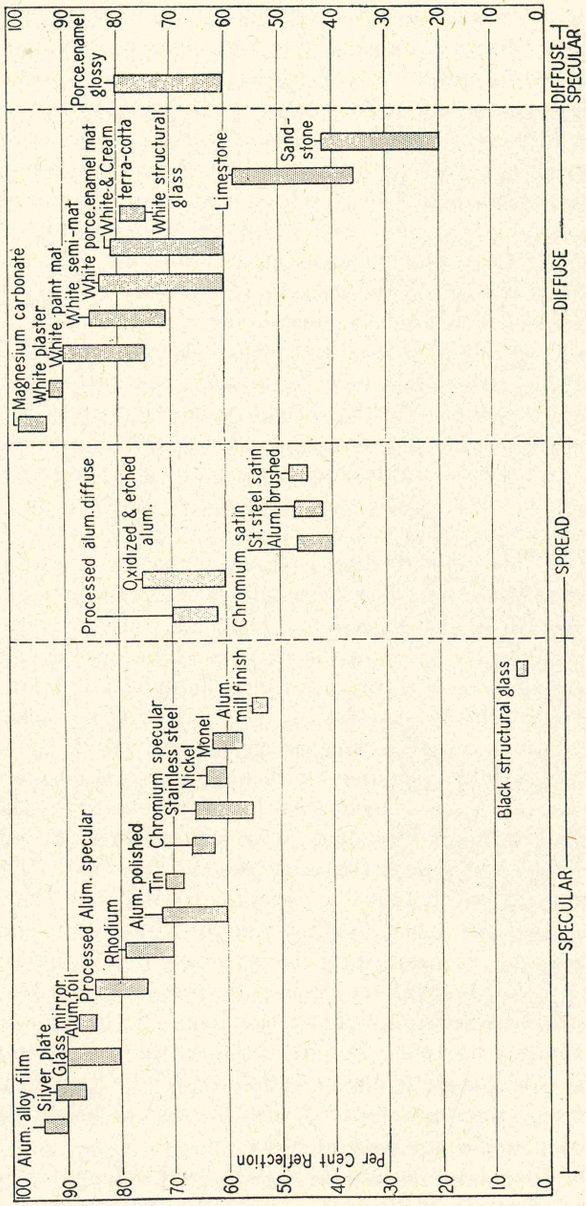


FIG. 100.—A classification of reflecting materials and an indication of their reflectivities.

and therefore the maximum beam candlepower is obtained with the specular finish. Both the diffuse and spread finishes have crosswise distributions similar to that of a typical diffusing reflector. These curves also illustrate the previously mentioned point that the area contained within the distribution curve is not a criterion of the output. The four distribution curves shown in Fig. 101 enclose considerably different areas, but the outputs are very comparable.

"Trapped" Light vs. "V" and Open-top Reflectors.—When a fluorescent lamp is mounted in a reflector, there is some light "trapped" between the lamp and the surface immediately above it. Actually, however, the loss is small because the fluorescent lamp absorbs only about 20 per cent of the light which is directed back upon it by the reflector section immediately above the lamp. Of the remaining 80 per cent, the surface of the lamp itself reflects about 60 per cent, 15 per cent passes through the lamp and builds up the candlepower being emitted from the other side of the bulb, and 5 per cent is reflected back in the general direction of the incident light.

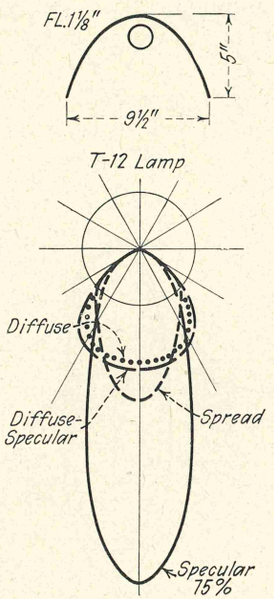


FIG. 101.—The effect of reflector finish on the distribution of a parabolic trough.

Nevertheless, many luminaire designers have attempted to increase the fixture output by placing a reflecting V immediately above the lamp. Figure 102 shows section view and crosswise distribution curves for two specular-parabolic contours, one having such a V insert and the other a 1⅞-in. opening at the top. Note that with the top closed the same curve and the same output are obtained with or without the V insert. Thus, the gain in output by using a V insert is usually very limited. On the other hand, the opening at the top results in a significant gain in output but with a decrease in downward light. And although the upward is not nearly so efficient in producing footcandles on the working plane, it does contribute to the appearance and atmosphere of the interior.

Another effect of leaving an opening at the top of the reflector is illustrated in Fig. 103 in which a specular reflector having a spread-ellipse contour and two sizes of top openings is employed. As might be expected, the unit efficiency increases as the width of the top opening is increased because reflecting surface is being eliminated (and there is always some absorption of light at every reflecting surface), the downward component, of course, decreasing as the width of the top opening increases.

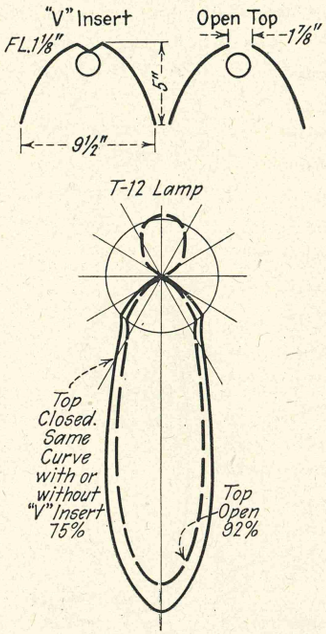


Fig. 102.—V inserts have little influence on the distribution or output of a specular parabolic reflector.

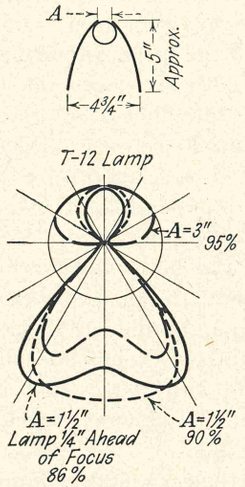


Fig. 103.—The effect of the size of the opening in the top of a specular spread-ellipse reflector.

Notice that of the three distribution curves shown in Fig. 103 the maximum spread up to the angle of total cut-off of the downward component is obtained with the lamp ¼ in. ahead of focus in the spread-ellipse contour. The result of having the lamp so positioned with respect to such a contour is that the near edge of the reflector cuts off the direct view of the lamp at the same angle at which it cuts off the reflected image in the far side of the reflector.

Nonsymmetrical Distributions.—Figure 104 shows two types of "combination" contours used to produce a nonsymmetrical

(asymmetrical) distribution of light for lighting show windows, store counters, switchboards, bulletin boards, etc. Note that the contour having an ordinary parabolic section on one side and a parabola tilted 5 deg. inward on the other results in a maximum beam candlepower higher than the parabola-spread ellipse combination, although slightly inferior from the shielding standpoint. Whereas this type of distribution could be obtained by simply tilting an ordinary symmetrical-distribution reflector, designs specifically for this service are more effective.

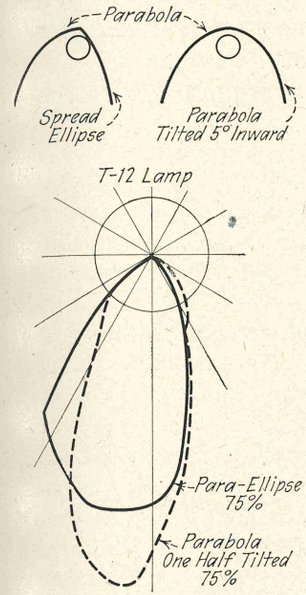


Fig. 104.—Two methods of obtaining asymetrical distributions from specular reflectors.

Flat-sectioned Contours.—Figure 105 shows that a fair degree of light

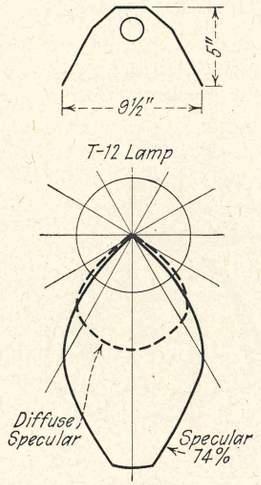


Fig. 105.—Stimulating a parabolic contour by flat-sided sections.

control may be obtained by carefully building up a flat section to approximate a given curvature (parabolic in this case). If less care is used, a wide distribution results.

Multiple-lamp Reflectors.—Figures 106, 107, and 108 are included simply to show the resulting distribution and output where in the interest of economy two lamps are used in one reflector. By comparing Fig. 108 with Fig. 96, it will be noted that the maximum candlepower is not much greater with two lamps in a specular parabolic section than with just a single lamp. This

fact is due to increased cross reflection and the less favorable positioning of the lamp (since only one can be at the focal point of the reflector). The candlepower at the wider angles, will, however, be considerably greater with the two-lamp unit.

Lenses.—Contrary to some earlier notions, the crosswise distribution of light from fluorescent lamps can be controlled by lens plates in which the prisms run parallel with the fluorescent

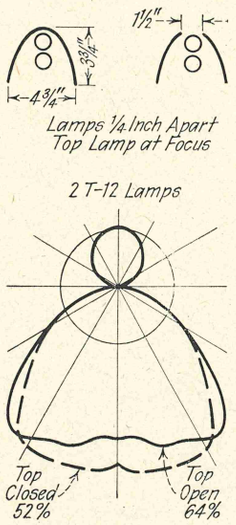


FIG. 106.

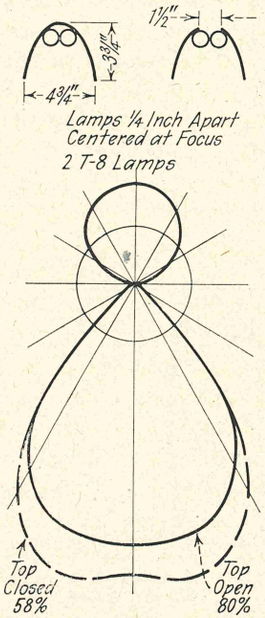


FIG. 107.

FIGS. 106 and 107.—A specular-spread elliptical reflector with two lamps positioned as shown.

lamp. The lens system may, in fact, result in better light control than from an open reflector.

The type of reflector to be used with lens-plate systems in securing reasonably high output depends on the application under consideration. For example, in those cases where it is not necessary to have a high concentration of light (downlighting of store counter tops, etc.), a parabolic type of reflector can be used in combination with a Fresnel type of extended lens. Where more accurate control is desired, an elliptical reflector can be

employed with the lamp at the first focal point and the focal point of the lens at the second focus of the ellipse.

Because of the characteristics of the fluorescent lamp, the circular trough reflectors (comparable to the spherical reflectors commonly used with filament-lens systems) are relatively ineffective. The contours described above are much more appropriate for fluorescent systems, and still higher efficiency can be secured at the sacrifice of some control by using large elliptical reflectors approaching a circular contour, properly positioned with respect to the lamp and the focal point of the lens plate.

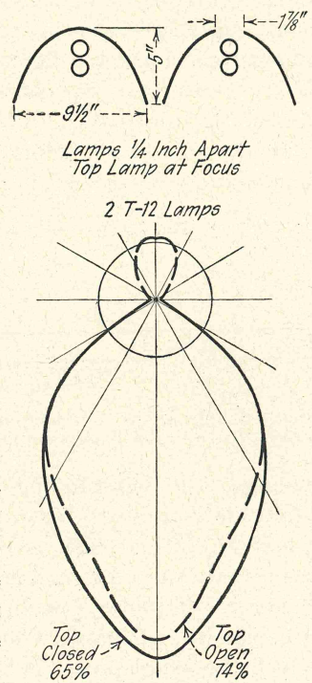


FIG. 108.—A specular parabolic reflector with two lamps positioned as shown.

Lens systems are flexible from the standpoint of moving the lamp laterally to change the angle of maximum candlepower. Lens plates having different types of distribution are also available.

Controlling Brightness to Secure Lighting Comfort.—Glare has been defined as *brightness* within the field of vision of such a character as to cause discomfort, annoyance, interference with vision, or eye fatigue. There are six principal factors that determine the degree to which glare is experienced. These are as follows:

1. The intrinsic brightness of the source.
2. Total amount of light emitted by the source in the direction of the eye.
3. The contrast in brightness between the light source and the working surfaces and surroundings.
4. The distance from the source to the eye.
5. The proximity of the light source to the line of vision.
6. The length of the time during which the source of glare is present within the field of vision.

These principles remain unchanged and still serve as valuable criteria in planning comfortable lighting systems. If a lighting system is also to provide conditions most favorable for seeing, there are other factors that must be considered, including the room size and proportions, the general brightness level in the room, and the character and severity of the visual task.

With all these various factors influencing the comfort and effectiveness of a lighting system, there is little wonder that some differences of opinion have occurred as to the position of fluorescent lamps and fluorescent lighting in the general realm of lighting comfort. Special attention should be called to item 6 under the principal factors that determine the degree to which glare is experienced. Some sources and conditions that are not immediately recognized as glaring may cause fatigue when within the field of vision for a considerable period of time. For example, the effect of looking out of a window for a moment is usually not at all unpleasant. But working all day at a desk facing that same window would probably be decidedly tiring. This is perhaps the outstanding reason why installations of bare-lamp luminaires are best avoided in those lighting applications where the visual task is relatively severe and prolonged—too many bare tubes become in time an annoyance to the eye.

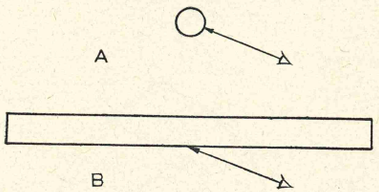


FIG. 109.—Crosswise (*A*) and lengthwise (*B*) viewing of fluorescent lamps.

Figure 109 shows two directions from which fluorescent lamps are viewed. *A* shows the crosswise viewing, the condition at which the candlepower in the direction of the eye is maximum, and *B* illustrates lengthwise viewing in which the lamp is foreshortened and both the total candlepower toward the eye and the brightness are reduced as the line of vision approaches the axis of the lamp. Crosswise and lengthwise distributions from a bare lamp were shown in Fig. 85 earlier in the chapter.

There are two methods of protecting the eye from the brightness of fluorescent lamps. One method is to introduce a refracting or diffusing medium through which the downward light must pass; the second is to provide shielding only at the higher angles by using louvers, baffles, or fixture cut-off itself.

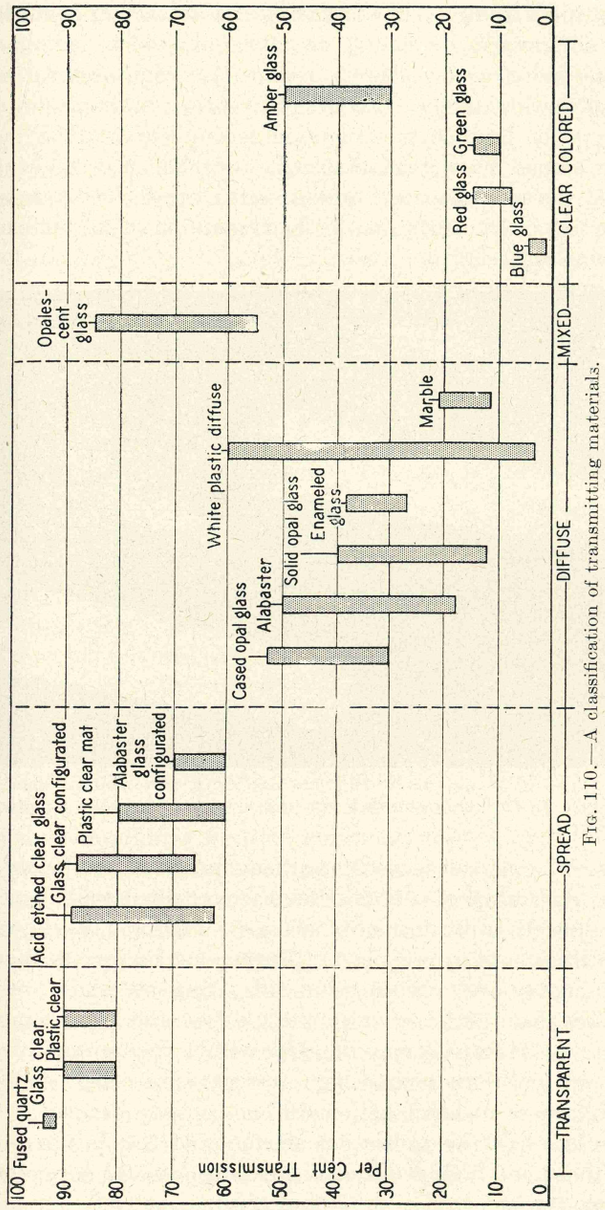


FIG. 110.—A classification of transmitting materials.

Brightness Reduction by Diffusing and Refracting Materials.—Many fluorescent luminaires are available which use plastic or diffusing or refracting glass to reduce the brightness within the normal viewing angles. Figure 117 shows a luminaire in which this type of brightness protection is employed. The light is simply spread over a greater area and thus the brightness is reduced. The more comfortable seeing conditions compensate for the loss in efficiency due to the absorption of the diffusing or refracting material.

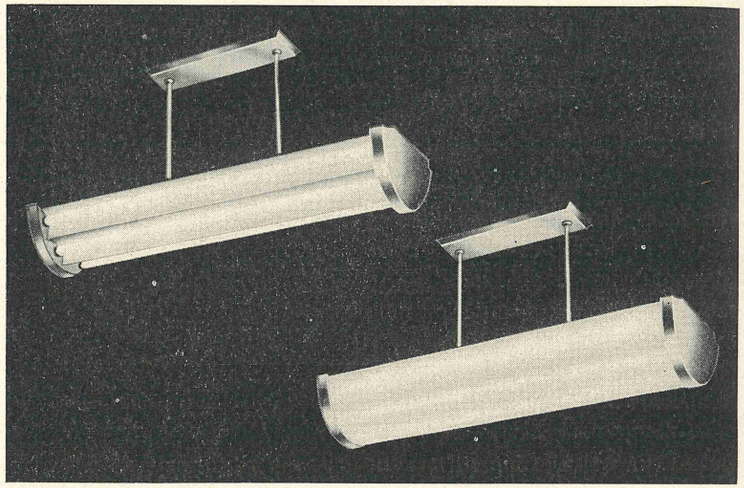


FIG. 111.—Bare-lamp units (left) are not much more glaring than poorly designed or inadequately shielded luminaires (right) from the standpoint of eye comfort.

Like reflecting surfaces, transmitting materials can be obtained with a wide range of characteristics from transparent clear glass to completely diffusing opal glasses. Figure 110 shows the classification and approximate transmission factors of many of the commonly used diffusing and diffracting materials.

Glasses that refract or only partly diffuse the light reduce the bare lamp brightness considerably within the normal viewing angle and yet have fairly high transmission. By using such material, more comfortable conditions can be obtained without serious losses in the utilization efficiency of the fixture. However, the more highly diffusing mediums should be employed when fluorescent lamps are completely surrounded, for in that

case the line of view is normal to the diffusing surface where the lamp brightness is least reduced. Figure 111 shows that there is little difference from the standpoint of eye comfort between exposed-lamp luminaires and poorly designed or insufficiently shielded luminaires.

Shielding with Louvers.—A louver is a shield used in a luminaire to intercept light traveling in undesired directions. Louvers are used either for the prevention of the glare, for more accurate control of the light, or for other reasons and may take various forms, the "egg-crate" type being perhaps the most common in fluorescent fixtures.

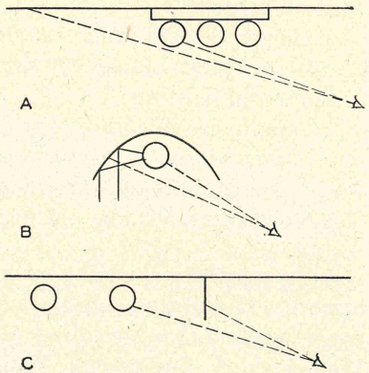


FIG. 112.—Three examples of bad brightness contrasts which should be avoided whenever possible.

In the many applications where reflected glare is not a serious problem because specular surfaces are not normally encountered, louvering is an excellent shielding device. The reflection factor of the louver should be as high as possible without its own surface becoming uncomfortably bright. Either opaque or translucent materials may be used as louvers. The depth of the louver is determined by the louver proportions and the shielding angle desired, by limits of desirable compromises with efficiency, and by the degree to which the reduction in vertical illumination is acceptable. The louver design also determines the "focusing" of the downward light and can affect the uniformity of the resultant illumination.

Brightness Contrast.—Brightness contrast is an important factor in producing glare. Figure 112 shows three examples of high brightness contrast which should be avoided whenever possible. *A* illustrates the objectionable result of installing bare fluorescent lamps on the ceiling. The contrast is usually too severe between the lamps (where viewing is crosswise and therefore maximum lamp brightness is seen) and the relatively dark ceiling beyond the lamps. *B* illustrates the result of using one type of specular reflector without adequate shielding, in which case too great a contrast exists between the lamp brightness and the low specular-

reflector brightness in the background. In *C*, there is a high contrast between the lamp and the opaque side of a fluorescent luminaire.

Recommended Shielding Angles.—In selecting fluorescent luminaires in which the shielding is provided by means of louvers or baffles, the following shielding angles[1] are recommended.

For office lighting:
  Lengthwise shielding—30 deg.
  Crosswise shielding—45 deg.
Store lighting:
  Lengthwise shielding—25 deg.
  Crosswise shielding—40 deg.
Industrial lighting:
  Lengthwise shielding—little if any is required, although units with closed ends do improve the comfort of continuous row installations at low mounting heights.
  Crosswise shielding—15 deg.

Although these shielding recommendations are suitable for the majority of lighting applications, there are, of course, certain cases where other shielding angles would be more desirable. Well-shielded fluorescent luminaires for commercial lighting are almost invariably more expensive and usually utilize the light less efficiently. Tests indicate that the comfort is improved if luminaires are shielded to an even greater extent than mentioned.

A Review of Fluorescent Luminaire Design.—On pages 148–155 will be found a description of 16 general types of luminaires and a tabulated appraisal of their appropriateness for the lighting various interiors.[2] In the latter respect, the following relative ratings are used: A, good; B, fair; C, poor.

[1] The shielding angle for fluorescent luminaires is that angle which will cut out the entire lamp (or lamps) from view in that direction. Lengthwise shielding means eliminating the view along the lamp axis from horizontal down to the given lengthwise shielding angle. Crosswise shielding means cutting off the view perpendicular to the lamp axis (where the brightness is maximum) from the horizontal down to the given crosswise shielding angle. Shielding is accomplished by the cut-off of the luminaire itself or by the appropriate use of louvers or baffles. Brightness control by other means has been discussed earlier in this chapter.

[2] Reprinted from *Magazine of Light*, No. 9, 1940.

It must be emphasized that the relative importance of the various criteria should be carefully weighed with respect to the particular problem at hand. For instance, in an office, the factors of major importance rank as follows:

1. Direct glare.
2. Reflected glare.
3. Illumination of the horizontal working plane.

On the other hand, in a factory, the order of importance might be[1]

1. Illumination on horizontal.
2. Illumination of vertical.
3. Maintenance.

In stores the order would generally be

1. Illumination on horizontal.
2. Shielding (direct glare).
3. Illumination on the vertical.

Approximate crosswise distribution curves, outputs, and Coefficients of Utilization are shown for each of the 16 general types. Complete tables of Coefficients of Utilization on many of these types will be found in Chap. VII where fluorescent-lighting design is more completely covered.

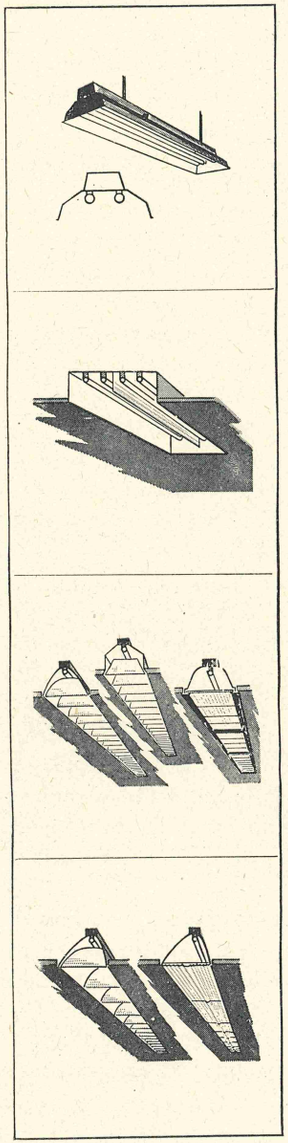
Figures 113 to 122 illustrate some of the fluorescent luminaires now commercially available. These are keyed to the general types previously discussed. Although space does not permit the illustration of all the many hundreds of luminaires now on the market, the ones shown are typical of the general types available.

RLM and Fleur-O-Lier Luminaires.—Not only must fluorescent luminaires be appraised on the basis of their illuminating quality, but the electrical and mechanical qualities also require attention. In fact, the latter is more important in the case of fluorescent equipment than for the simpler luminaires that suffice for filament lamps.

Besides relying on the name and reputation of well-known manufacturers, buyers of fluorescent fixtures are offered labels of the RLM and Fleur-O-Lier groups as indication of quality and design. These groups supply laboratory-tested products, and the certification labels serve as guideposts to the customer and assist him in the selection of fluorescent equipment. (*Text continues on page 159.*)

[1] Direct glare would certainly also be an important consideration in industrial lighting.

A REVIEW OF FLUORESCENT LUMINAIRE DESIGN



1. Two-lamp Porcelain-enameled Reflector

Protection from Glare.—Sides of reflector shield lamps from direct view crosswise to angle of 15 deg. or more below horizontal. Closed ends provide some shielding in lengthwise direction.

Applications.—Industrial interiors, warehouses, stockrooms, etc.

Maintenance.—Little dust collection, easy cleaning and lamp replacement.

2. Open Coffer or Suspended Trough

Protection from Glare.—Crosswise shielding is dependent upon depth of coffer. If more than two rows of lamps are used, it is generally desirable to employ a lengthwise baffle similar to that shown.

Applications.—Industrial interiors; warehouses; certain types of store interiors, particularly narrow, high-ceiling areas where endwise viewing predominates; corridors; etc.

Maintenance.—The closed top and lack of dust-retaining surfaces are conducive to good maintenance. Lamp renewal and cleaning are easy.

3. Troffers: Spread or Diffuse Reflectors with Louvers and Specular Reflector with Lens Plates

Protection from Glare.—Sides of louvered troffers provide shielding in crosswise direction (usually 45 deg. below horizontal); louvers provide shielding in lengthwise direction (30 deg. below horizontal) which is satisfactory for most critical seeing tasks. Diffuse aluminum reflectors preferable to matte white because of their reduced contrast with ceiling. Louvers, if opaque, should have a surface with diffuse or spread reflection characteristics. Protection with lens plates depends upon several factors. In some cases it may be desirable to add a supplementary system to light the ceiling and reduce harsh contrasts of brightness.

Applications.—Offices; schools; industrial; stores—to direct light onto selling and display areas.

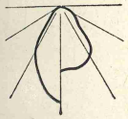
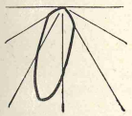
Maintenance.—Surfaces are vertical and therefore tend to collect little dust. May be easily cleaned; if provision is made for removing louvers, relamping may readily be accomplished. For troffers with lens plates, the discussion under type 5 applies.

4. Controlling Asymmetrical Specular Reflector with Louvers or Lens Plates

Protection from Glare.—Sides of reflectors and louvers provide shielding adequate for merchandising interiors (30 to 40 deg. crosswise, 15 to 25 deg. lengthwise, below horizontal). Asymmetric reflector permits placing unit so that reflected glare is minimized when surface to be lighted is glass or polished. The comments on reducing contrast with ceiling given for fixture type 3 apply here also. The lens helps to provide control and furnishes adequate lengthwise and crosswise shielding.

Applications.—Units of this type provide an excellent way of directing considerable light to specific display and selling areas. They also furnish a solution to similar industrial and office lighting problems.

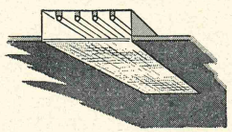
Maintenance.—The considerations given for louvered type 3 and enclosed type 5 apply here also.

Approximate crosswise distribution, output and utilization (all Coefficient of Utilization values for 75 % ceiling, 30 % walls)	Important factors to be considered	Office and school	Merchandising	Industrial	Casual seeing
Output 75–80 % Utilization For Room Index J: 0.30 For Room Index A: 0.70	Direct glare	*	*	A–B	B
	Reflected glare	*	*	A–B	†
	Maintenance	*	*	A	A
	Illumination on horizontal	*	*	A	A
	Illumination on vertical	*	*	A	A
	Appearance of lighted room	*	*	A	B–C
Output 70–75 % Room Index J: 0.30 Room Index A: 0.65	Direct glare	*	B	A–B	B
	Reflected glare	*	†	A–B	†
	Maintenance	*	A	A	A
	Illumination on horizontal	*	A	A	A
	Illumination on vertical	*	A	A–B	A
	Appearance of lighted room	*	B	A	B–C
 Output 60–65 % Room Index J: 0.30 Room Index A: 0.60	Direct glare	A–B	A	A	A
	Reflected glare	B	†	A–B	†
	Maintenance	A–B	A–B	B	A–B
	Illumination on horizontal	A	A	A	A
	Illumination on vertical	A	C	C	A–B
	Appearance of lighted room	A–B	A–B	A	A–B
 Output with louvers 70–75 % With lens 60–65 %	Direct glare	‡	A	‡	‡
	Reflected glare	‡	†	‡	‡
	Maintenance	‡	A–B	‡	‡
	Illumination on horizontal	‡	A	‡	‡
	Illumination on vertical	‡	A	‡	‡
	Appearance of lighted room	‡	A	‡	‡

* Not recommended.

† Not usually of major importance. In stores, however, high lights are sometimes desirable, particularly in the display of polished surfaces.

‡ Not generally used. Applicable for specialized conditions.

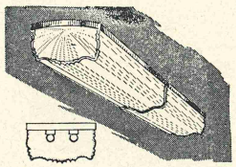


5. Flush or Suspended Unit with Refracting Glass Panel

Protection from Glare.—Brightnesses at higher angles (direct glare) are reduced considerably, and with some glasses those at the lower angles (reflected glare) are also diminished appreciably. More diffusing glasses provide very good brightness control but reduce output. Lamp centers should be 2 in. or more above the glass, and luminous sides or a supplementary system directing some light to the ceiling and walls are desirable so as to relieve possible harsh brightness contrasts.

Applications.—Stores. Glasses providing considerable diffusion suitable for offices.

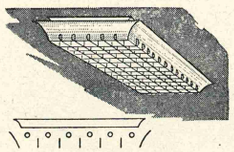
Maintenance.—A horizontal surface is inherently dust-collecting; the depreciation, however, depends upon the tightness of joints. The glass bottom should be hinged or otherwise easily removable to permit easy cleaning and lamp replacement.



6. Semi-direct Unit Enclosed with Diffusing Glass

Protection from Glare.—These units present large areas of brightness in the normal field of view. This brightness is generally satisfactory for most store services. In general, they are less suitable for most school and office applications. They are excellent for coordination with architectural elements.

Maintenance.—These units are closed at the top and the comments for type 5 apply. Care must be taken that lamp temperatures do not become excessive and cause a serious reduction in light output.



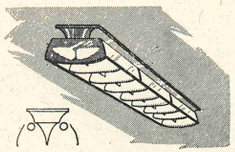
7. Ceiling-mounted Semi-direct Unit with Translucent or Opaque Sides and Louvers

Protection from Glare.—Degree of shielding (45 deg. crosswise, 30 deg. lengthwise below horizontal) satisfactory for offices. Less shielding (30 to 40 deg. crosswise and 15 to 30 deg. lengthwise) suitable for many stores.

If sides and louvers are translucent, transmission factor may be as high as 60%. Luminous sides mitigate somewhat deficiency in illumination of vertical surfaces and contrast with ceiling. If sides and louvers are opaque, their surfaces should have diffusing or spread reflection characteristics, never specular.

Distribution.—The greater the shielding, the more concentrated the distribution, thereby reducing illumination on vertical surfaces.

Maintenance.—Vertical surfaces conducive to good maintenance. Louvers should be constructed to permit easy cleaning and lamp replacement.

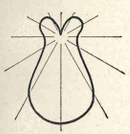


8. Ceiling Mounted Semi-direct Unit with Diffuse or Spread Surface Reflectors; Plastic Sides; Crosswise Louvers

Protection from Glare.—The plastic sides and central member furnish shielding for crosswise view. The louvers shield for lengthwise view. The design of the upper part of the reflector is such as to direct light to the ceiling, thus eliminating objectionable ceiling contrasts.

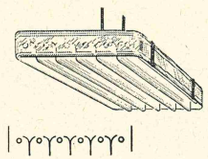
Applications.—Suitable for store applications, from the standpoint of distribution and appearance, especially when the 100-watt fluorescent lamps are employed.

Maintenance.—Easy relamping through the top. The vertical surfaces are conducive to good maintenance.

Approximate crosswise distribution, output, and utilization (all Coefficient of Utilization values for 75% ceiling, 30% walls)	Important factors to be considered	Office and school	Merchandising	Industrial	Casual seeing
Output 50–60% Utilization For Room Index J: 0.25 For Room Index A: 0.50	Direct glare	B	A	A	A
	Reflected glare	A–B	†	A	†
	Maintenance	B	B	B–C	B
	Illumination on horizontal	B–C	B–C	B–C	B–C
	Illumination on vertical	A	B	B	A
	Appearance of lighted room	A–B	A–B	A	A–B
Output 50–60% Utilization For Room Index J: 0.20 For Room Index A: 0.45	Direct glare	C	B	*	A
	Reflected glare	B	†	*	†
	Maintenance	B	B	*	B
	Illumination on horizontal	B–C	B–C	*	B–C
	Illumination on vertical	A	A	*	A
	Appearance of lighted room	B–C	A–B	*	B
Output 65–75% Utilization For Room Index J: 0.30 For Room Index A: 0.60	Direct glare	A–B	A	*	A
	Reflected glare	B	†	*	†
	Maintenance	B	B	*	B
	Illumination on horizontal	A	A	*	A
	Illumination on vertical	A	B	*	A
	Appearance of lighted room	A–B	A	*	A–B
 Output 70–75% Utilization For Room Index J: 0.25 For Room Index A: 0.55	Direct glare	A–B	A	*	A
	Reflected glare	B	†	*	†
	Maintenance	A	A	*	A
	Illumination on horizontal	B	B	*	B
	Illumination on vertical	A	B	*	A
	Appearance of lighted room	A	A	*	A

* Not recommended.

† Not usually of major importance. In stores, however, high lights are sometimes desirable, particularly in the display of polished surfaces.



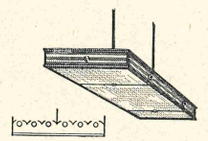
9. Suspended Semi-direct Unit with Semi-concentrating or Widespread Reflectors Slotted at the Top; Open Bottom; Etched Glass or Opaque Sides; Glass or Metal Baffles Lengthwise between Adjacent Lamps

Protection from Glare.—The sides of the unit and the baffles between adjacent lamps provide sufficient crosswise shielding for most merchandising applications.

Distribution.—Luminous sides are generally preferable to opaque sides in this unit because they increase the amount of light available for the illumination of vertical surfaces.

Applications.—Merchandising interiors; with cross louvering and glasses providing considerable diffusion suitable for offices.

Maintenance.—Vertical surfaces conducive to good maintenance. Cleaning and relamping can be done readily.

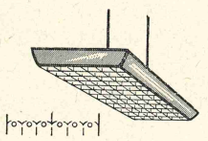


10. Suspended Semi-direct Unit with Semi-concentrating Reflectors, Slotted at the Top; Opaque or Luminous Sides; Etched Configurated Glass Bottom, Configurated Plastic, etc.

Protection from Glare.—In general, satisfactory brightness control can be obtained with glasses of this type if the lamps are located a few inches (2 in. or more) above the glass. The brightnesses at the higher angles (direct glare) are reduced considerably and with some glasses those at the lower angles (reflected glare) are also diminished appreciably.

Applications.—Stores; glasses providing considerable diffusion suitable for offices.

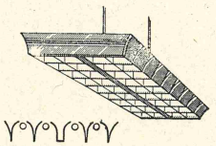
Maintenance.—Open top and closed bottom conducive to collection of dust. Glass bottom should be hinged to facilitate cleaning and relamping. With this type of unit a regular maintenance schedule is most important to insure continued good output and appearance.



11. Suspended Semi-direct Unit with Semi-concentrating Reflectors, Slotted at the Top; Opaque or Luminous Sides; Louvered Bottom

For comments on shielding and applications, see those given for type 7.

Maintenance.—Some provision should be made for lamp replacement, probably most conveniently done through top of reflectors.



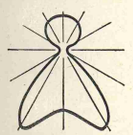
12. Suspended Semi-direct Unit with Deep Elliptical Reflectors Providing Control and Crosswise Shielding, and Slotted at the Top to Furnish Upward Light

Protection from Glare.—The reflectors are designed to produce sufficient crosswise shielding, and louvers are inserted to take care of lengthwise view. In addition, the lamp is so positioned with respect to the specular reflector that the lamp and its image are cut off at the same angle. This minimizes the common disturbing contrasts between the bright source and the dark reflectors.

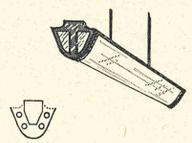
Distribution.—The size of the openings in the tops of the reflectors determines the amount of upward light. Good vertical illumination is obtained.

Applications.—Suitable for the lighting of merchandising areas and offices, depending upon brightness protection provided.

Maintenance.—Lamp replacement is through the openings in the tops of the reflector. The open bottom allows most of the dust to drop through.

Approximate crosswise distribution, output, and utilization (all Coefficient of Utilization values for 75% ceiling, 30% walls)	Important factors to be considered	Office and school	Merchandising	Industrial	Casual seeing
Output 80–85% Utilization For Room Index J: 0.30 For Room Index A: 0.65	Direct glare	B–C	B	....	A
	Reflected glare	B	†	....	†
	Maintenance	A	A	....	A
	Illumination on horizontal	A	A	....	A
	Illumination on vertical	A	A–B	....	A
	Appearance of lighted room	A–B	A	....	A
Output 70–75% Utilization For Room Index J: 0.30 For Room Index A: 0.60	Direct glare	B	A	....	A
	Reflected glare	A–B	†	....	†
	Maintenance	C	C	....	C
	Illumination on horizontal	A	A	....	A
	Illumination on vertical	A	B	....	A
	Appearance of lighted room	A	A	....	A
Output 65–70% Utilization For Room Index J: 0.25 For Room Index A: 0.55	Direct glare	A–B	A	....	A
	Reflected glare	B	†	....	†
	Maintenance	B	B	....	B
	Illumination on horizontal	B	B	....	B
	Illumination on vertical	B	C	....	B
	Appearance of lighted room	A	A	....	A
 Output 75–80% Utilization For Room Index J: 0.30 For Room Index A: 0.60	Direct glare	A–B	A	....	A
	Reflected glare	B	†	....	†
	Maintenance	A–B	A–B	....	A–B
	Illumination on horizontal	A	A	....	A
	Illumination on vertical	A	A–B	....	A
	Appearance of lighted room	A	A	....	A

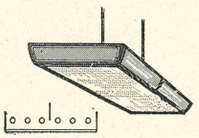
† Not usually of major importance. In stores, however, high lights are sometimes desirable, particularly in the display of polished surfaces.



13. Suspended or Ceiling Mounted, Etched Glass or Plastic Unit with Open Top

Protection from Glare.—The large area of brightness such units present in the normal field of view makes them less suitable for most school and office applications. When lamps are spaced well behind the glass or plastic shield, this brightness is generally satisfactory for many store services, particularly the smaller areas, and especially when the axis of the unit parallels the usual line of sight.

Maintenance.—Dust collects on the inside of the unit because of the open top. Lamp replacement and cleaning is ordinarily more difficult than with other types, although, if the bottom part of the unit is hinged, these become relatively simple tasks. Volume of unit should be large enough to prevent excessive lamp temperatures and resulting decrease in light output.

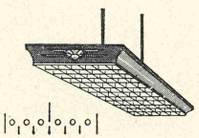


14. Suspended Semi-indirect Unit with Open Top; Opaque or Luminous Sides; Configurated Glass Bottom

Protection from Glare.—Same as for type 10.

Applications.—Stores; also suitable for offices, with glasses providing considerable diffusion.

Maintenance.—Same as for type 10, though cleaning and relamping are readily accomplished from above.

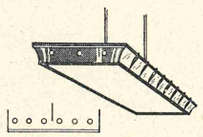


15. Suspended Semi-indirect Unit with Open Top; Opaque or Luminous Sides; Louvered Bottom

Protection from Glare.—The comments on shielding given for type 7 apply here.

Applications.—Offices, schools, and stores.

Maintenance.—Very little dust collection because of the open louvered bottom. Relamping usually can be accomplished readily from above.

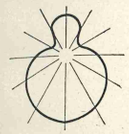
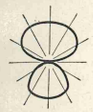
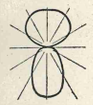


16. Suspended Semi-indirect Unit with Open Top; Opaque or Luminous Sides; Highly Diffusing Glass Bottom

Protection from Glare.—With the lamps located a reasonable distance above the glass, the diffusing bottom plate provides very good brightness control.

Applications.—Suitable for office and school applications.

Maintenance.—Same as for types 10 and 14.

Approximate crosswise distribution, output, and utilization (all Coefficient of Utilization values for 75% ceiling, 30% walls)	Important factors to be considered	Office and school	Merchandising	Industrial	Casual seeing
 Output 65–70% Utilization For Room Index J: 0.20 For Room Index A: 0.50	Direct glare	C	B	....	A–B
	Reflected glare	B	†	....	†
	Maintenance	C	C	....	C
	Illumination on horizontal	B–C	B–C	....	B–C
	Illumination on vertical	A	A	....	A
	Appearance of lighted room	B–C	A	....	B
 Output 80–85% Utilization For Room Index J: 0.25 For Room Index A: 0.55	Direct glare	B	A	....	A
	Reflected glare	A–B	†	....	†
	Maintenance	C	C	....	C
	Illumination on horizontal	B	B	....	B
	Illumination on vertical	A	B	....	A
	Appearance of lighted room	A	A	....	A–B
 Output 70–75% Utilization For Room Index J: 0.20 For Room Index A: 0.50	Direct glare	A–B	A	....	A
	Reflected glare	B	†	....	†
	Maintenance	A–B	A–B	....	A–B
	Illumination on horizontal	B–C	B–C	....	B–C
	Illumination on vertical	A	B	....	A
	Appearance of lighted room	A	A	....	A
Output 75–80% Utilization For Room Index J: 0.20 For Room Index A: 0.50	Direct glare	A	A	....	A
	Reflected glare	A	†	....	†
	Maintenance	C	C	....	C
	Illumination on horizontal	B–C	B–C	....	B–C
	Illumination on vertical	A	B	....	A
	Appearance of lighted room	A	A	....	A

† Not usually of major importance. In stores, however, high lights are sometimes desirable, particularly in the display of polished surfaces.

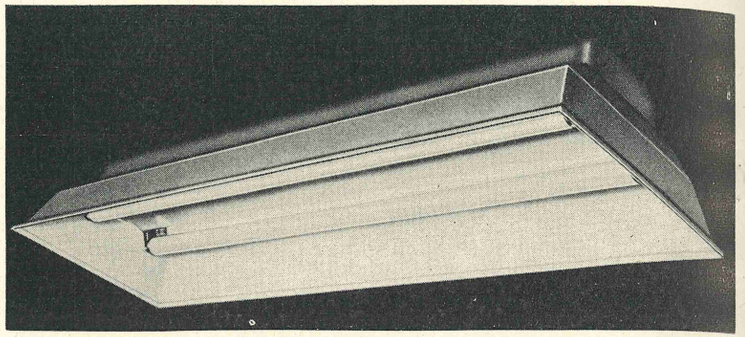


FIG. 113.—The standard 40-watt RLM fluorescent luminaire. Similar to type 1.

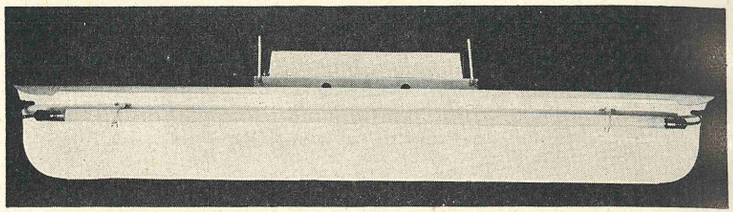


FIG. 114.—A Type RF luminaire tipped slightly to show the lamp details. Similar to type 1.

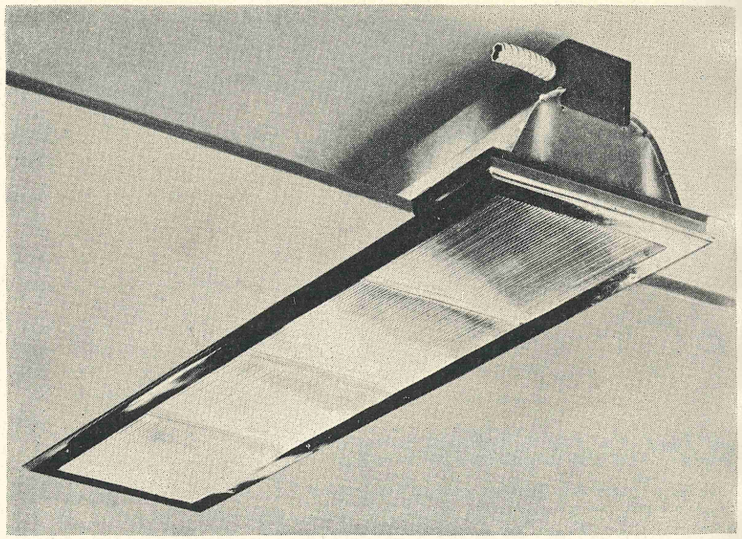


FIG. 115.—A lens-covered troffer. Similar to type 4 but with symmetrical reflector. Brightness and candlepower control provided by lens.

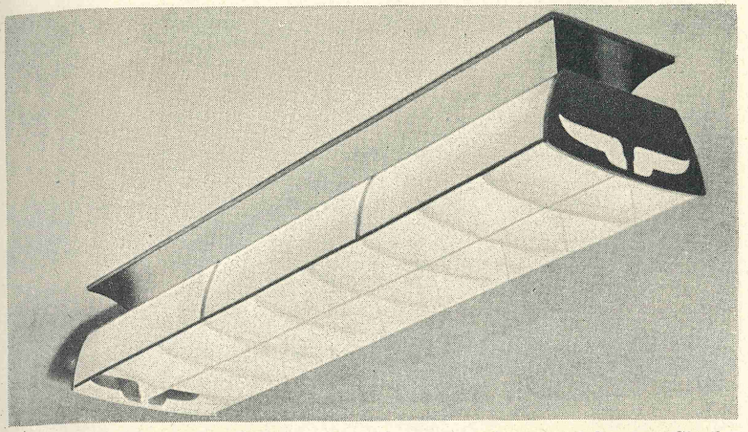


FIG. 116.—A luminaire designed for two 100-watt fluorescent lamps. Similar to type 8.

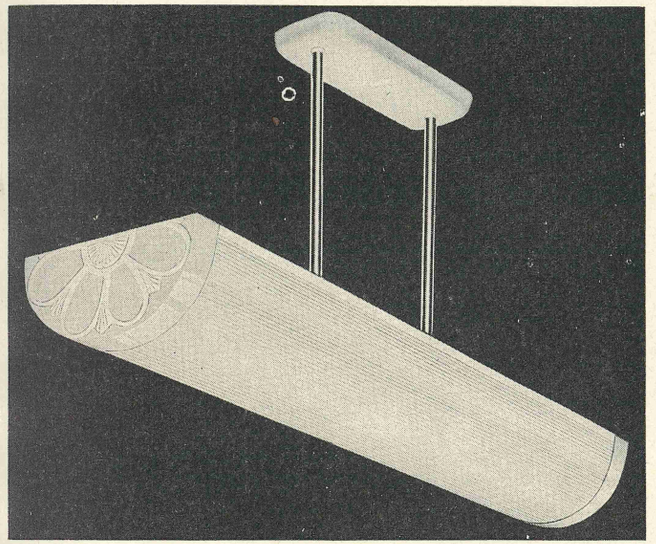


FIG. 117.—The familiar half-cylinder luminaire having an internal reflecting surface and shielding material of diffusing glass or plastic removable for lamp replacement. Similar to type 13.

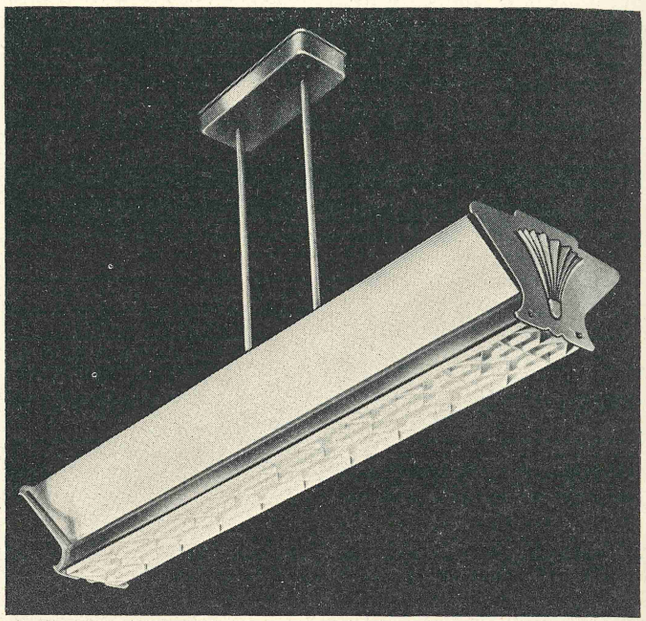


FIG. 118.—Similar to type 13 although open louvered bottom increases the amount of downward light and lessens dust accumulation.

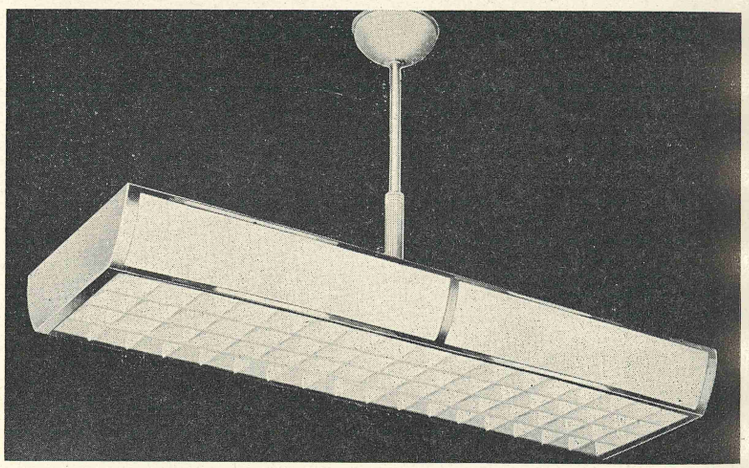


FIG. 119.—A direct-indirect luminaire having an open top, translucent sides and louvered bottom. Similar to type 15.

Fleur-O-Lier specifications cover equipment design for a wide variety of services, and the specifications are, of necessity, somewhat general in character. Specifications of the RLM Standards Institute covering RLM fluorescent luminaires are more detailed and precise, for these equipments are largely confined to indus-

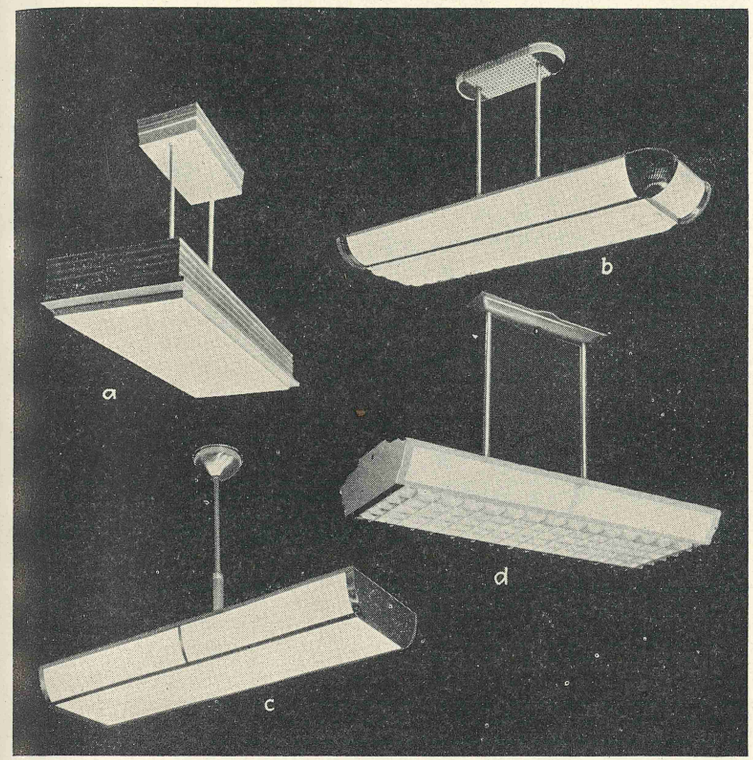


FIG. 120.—Some other typical direct-indirect luminaires for fluorescent lamps: (*a*) similar to type 11 but with opaque sides, (*b*) similar to type 15—this particular luminaire has circular interlocking louvers at the bottom, (*c*) similar to type 16, and (*d*) similar to type 15.

trial lighting. Both of these labels indicate that the equipment has passed electrical and mechanical specifications and certain specifications as to its illuminating qualities as well. Both services are open to reputable fixture manufacturers whose products meet the specifications.

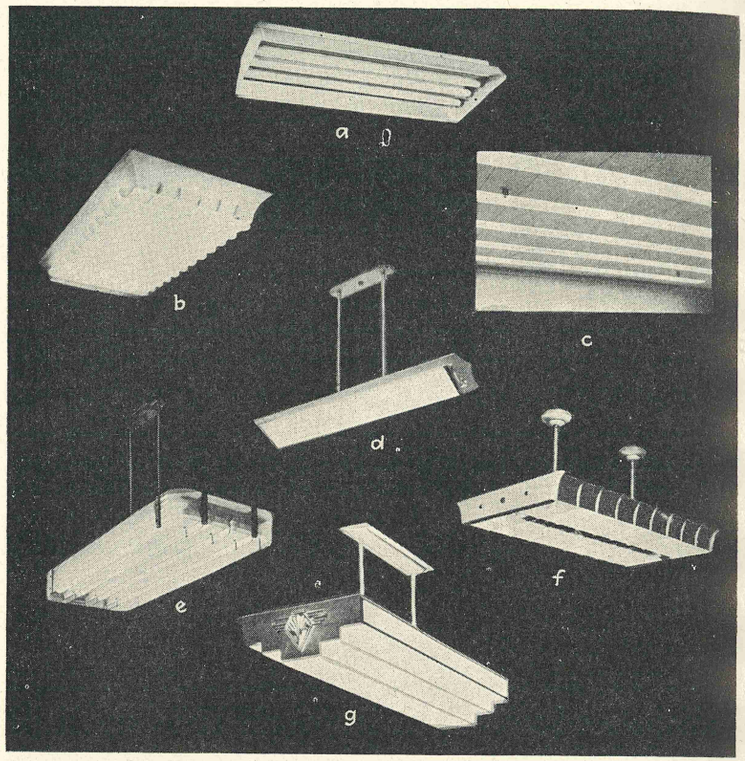


FIG. 121.—Miscellaneous fluorescent luminaires of the types commonly encountered. The units illustrated are similar to the following general fixture types: (*a*) type 1, (*b*) type 7, (*c*) type 3, (*d*) type 13, (*e*) type 9, (*f*) type 12, (*g*) type 11 or 15.

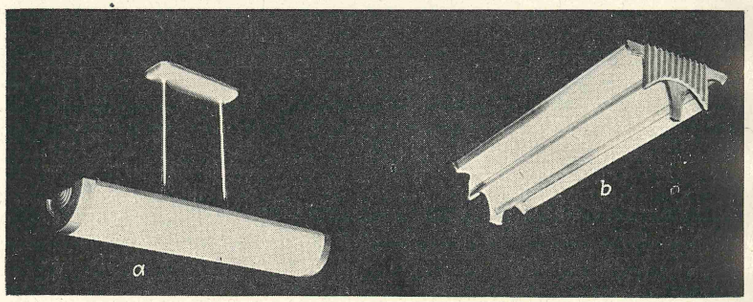


FIG. 122.—Other typical fluorescent luminaires: (*a*) similar to type 13, and (*b*) comparable in many respects to type 8.

CHAPTER VII

FLUORESCENT LIGHTING DESIGN

Footcandle Levels in Modern Lighting Practice.—Although the eyes are capable of adapting themselves to illumination levels ranging from a small fraction of a footcandle to several thousand footcandles, under very low levels they simply do not receive sufficient light to enable them to distinguish color or detail. At the other extreme, the blinding effect of unusually brilliant sunlight (6000 to 10,000 footcandles on a clear day) may not be conducive to comfortable seeing. Between these limits, there is a wide range where good vision is possible.

Many years of lighting research and numerous field tests prove that if the illumination is satisfactory as regards quality, *i.e.*, well-diffused and with no extreme brightness contrasts between the surface to be looked at and its surroundings, it is difficult indeed to provide too much light for the eyes. Minimum footcandle recommendations have always been based on considerations of economy and the availability of equipment to provide those recommended footcandle levels with comfort. But the fact of the matter is that just as light enables people to see, so more and better light means more accurate and easier seeing. Actually, the reservoir of knowledge built up by the hundreds of experiments on the relation of light to seeing gives the lighting man more justification for recommending 100 or more footcandles today than he had in prescribing 5 footcandles or less two decades ago.

Much of this knowledge has been given to the public in a popular form through the Better Light–Better Sight movement. As a result, most people realize the value of more and better light, and the introduction of a light source of higher efficiency usually results in improvements in the generally accepted footcandle levels.

In industry, for example, where the emphasis at present is on greatly increased production yet with no sacrifices in accuracy

and quality, present lighting installations show a marked trend toward the higher illumination levels. When new plants are built, there is no question any more about whether good modern lighting is a safe investment. It is simply taken for granted that 50 footcandles of general illumination for normal production work is a necessity, for it stops waste motion. Older installations are being relighted to this illumination level or

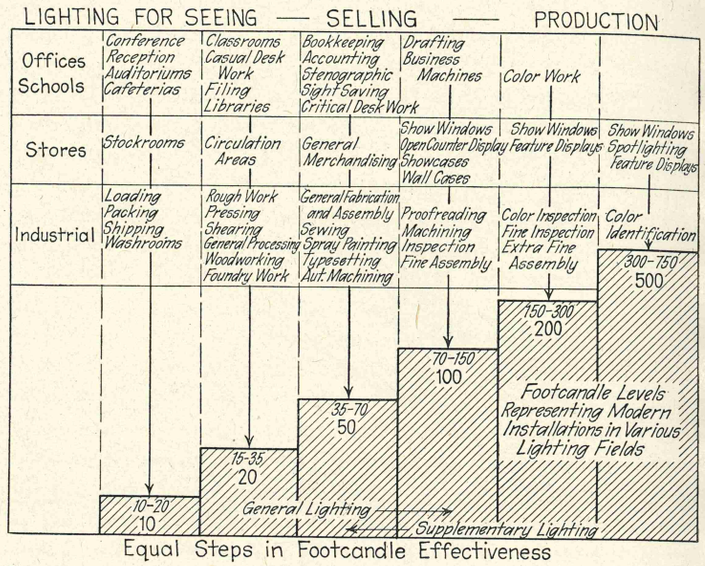


FIG. 123.—Recommended footcandle charts are easily adapted to a "step" type of diagram because existing footcandle levels must be at least doubled to secure significant and measurable improvements in illumination effectiveness. This chart illustrates the footcandle levels which represent modern lighting installations in various types of interiors.

higher. And with the cost of good lighting now lower than ever before because of increased lamp efficiency, reduced electric rates, and decreased lamp prices, these footcandle levels can now be economically attained.[1]

One of the important principles disclosed by the science of seeing is that where significant and measurable improvements in illumination effectiveness are to be expected the existing footcandle level should at least be doubled. This logarithmic progression lends itself to a "step" type of diagram to represent

[1] See Chap. X.

acceptable illumination levels. Figure 123 shows such a chart and indicates the general footcandle levels being employed in

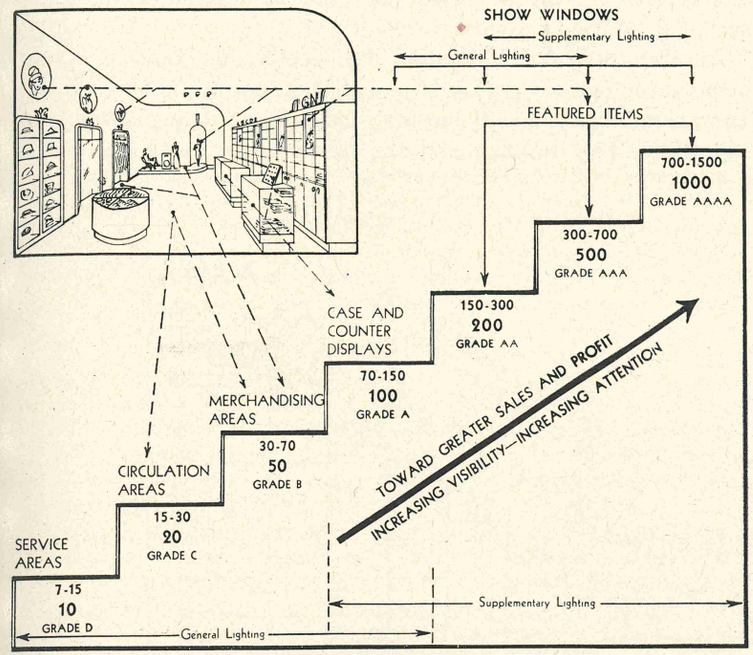


FIG. 124.—A step diagram of the footcandle levels representative of modern store-lighting practice.

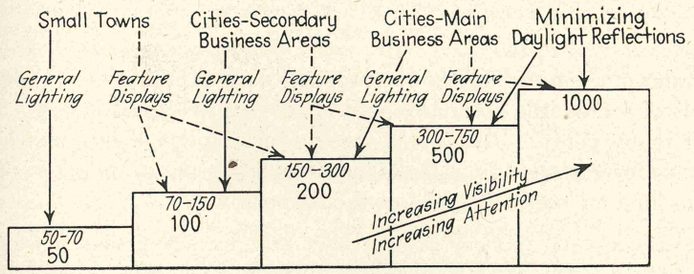


FIG. 125.—Footcandle standards for show windows.

practical lighting applications. Figure 124 shows a similar chart devoted exclusively to store lighting and Fig. 125 to show windows. As representative of modern lighting practice, these

charts can be utilized in making normal footcandle recommendations, with the confidence that many similar recommendations have been previously made and the results enthusiastically accepted by the customer.

Another diagram indicating the footcandle ranges recommended for various grades of seeing tasks set up on the basis of approximately equal steps in footcandle effectiveness is shown in Fig. 126. The diagram and the following explanations of the

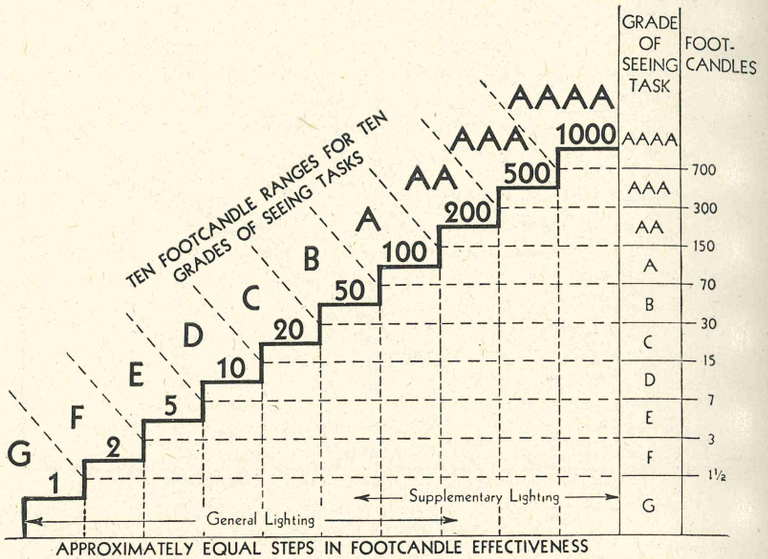


FIG. 126.—A general diagram showing the 10-footcandle ranges for various grades of seeing tasks.

grades of seeing represent the most modern thinking on the subject of footcandle standards and should be in "good company" for many years.[1] The more specific recommended illumination levels for various seeing tasks in particular types of interiors will be found on pages 292–303 of the Appendix.

Grade A[2]—100 *Footcandles.*—For very exacting and prolonged seeing tasks such as fine bench and machine work, extra fine hand painting and

[1] WALTER STURROCK, "Recommended Levels of Illumination," *Magazine of Light*, No. 6, 1941.

[2] This level is about 10 per cent of outdoor illumination on an average overcast day.

finishing, and for the discrimination of fine detail of low contrast as in pressing dark cloth products and weaving dark woolens. For showcases, wall cases, and open counter displays in stores where discrimination of detail and attention value are important factors. (Under varying circumstances, the footcandles may range from 30 per cent below to 40 per cent above the value given.)

Grade B—50 *Footcandles.*—For severe and prolonged seeing tasks such as medium bench and machine work, medium fine assembly and inspection, fine sanding and finishing woodwork, drafting, and proofreading. For general merchandising areas in stores and for show windows in small towns. (Range—minus 30 per cent to plus 40 per cent.)

Grade C—20 *Footcandles.*—For moderately critical and prolonged seeing tasks such as rough bench and machine work, medium assembly and inspection, hand painting and finishing, for pressing light cloth products, and weaving light woolens. For circulation areas in stores. (Range—minus 30 per cent to plus 40 per cent.)

Grade D—10 *Footcandles.*—For visually controlled work in which seeing is important but more or less interrupted or casual and does not involve discrimination of fine details or low contrasts; for rough manufacturing processes such as molding clay products and cements, glass-blowing machines, billet, blooming, and sheet-bar mills in steel manufacturing. For stock rooms and active storage areas for a variety of small articles such as for merchandising stocks.

Grade E—5 *Footcandles.*—For interiors where crude manual tasks are intermittently carried on, such as required for grinding clay products and cements, stone crushing, hand furnaces and boiling tanks in chemical plants, stock rooms, and active storage areas for medium-sized materials; for the safe assembly or movement of people in auditoriums, through corridors, and stairways. For active work areas out of doors, such as loading docks.

Grade F—2 *Footcandles.*—For rough outdoor work such as in dredging and in stone quarries and for seating areas during baseball, boxing, and other outdoor sports.

Grade G—1 *Footcandle.*—To dispel darkness in large outdoor areas, such as for bathing beaches, for automobile parking, lumber and other storage yards, and for industrial protective lighting.

Grade AA—200 *Footcandles.*—For extra-fine inspection such as required in making jewelry and precision instruments. For featured items and merchandise displays in show windows in secondary business areas of large cities. (Range—minus 30 per cent to plus 40 per cent.)

Grade AAA—500 *Footcandles.*—For feature merchandise displays in show windows in main business areas of large cities. For color identification in industry. (Range—minus 30 per cent to plus 40 per cent.)

Grade AAAA—1000 *Footcandles.*—Outdoor levels of illumination. For photography, hospital operating rooms, and the daytime illumination of show windows. (Range—minus 30 per cent to plus 40 per cent.)

The Advantages of Modern Illumination Levels.—Higher footcandle levels bring many benefits. For example:

In the store, higher footcandles will
- Increase sales—more than enough to pay for the better lighting.
- Decrease returned merchandise—saving customer's time and merchant's money.
- Increase prestige—by improving the store appearance.
- Reduce selling time required.

In the office and school, improved lighting gives
- More accurate work—saves time, money, and good will.
- Increased efficiency—more productive (and thus profitable) work.
- Eyesight, health, and energy conservation—modern lighting's humanitarian values.

In the factory, more light for production gives
- Improved quality—accurate seeing gives greater uniformity.
- Increased production—for more profit and to reduce backlogs.
- Decreased cost—less spoilage, fewer rejects, fewer accidents.
- Improved employee morale, better use of floor space, and lower maintenance cost.

Black-out Levels in Contrast.—Although lighting people universally recognize the value of more and better light, it is interesting to compare the footcandle levels in Figs. 123 to 126 with those which of necessity must be employed during nighttime hours to cope with war conditions. The lighting problems that have arisen in connection with air-raid precautions are beyond the scope of this manual, but the regulations limit lighting to such low levels of magnitude that they are included here for the sake of curiosity. At least they seem to instill an appreciation of our heritage of abundant light—which, like so many other things, goes almost unnoticed until it is no longer available.

At this writing,[1] general black-out specifications have not been released by United States military authorities. Such specifications will be available from local civilian defense officials when they are released. The following summary of British ARP regulations indicates the measures taken to meet such situations over there and must not be construed as United States specifications or recommendations.

For example, the basis of ARP (Air Raid Precaution) lighting in Great Britain is the complete black-out. Interior lighting must be so screened as to be invisible from the ground or the air, and exterior lighting, where permitted, is regarded as an exception to the general rule. Such exterior lighting is generally

[1] February, 1942.

permitted only in certain circumstances for essential operations, such as work in docks and railway yards, for street lighting, and for essential signs and aids to movement. Because an air observer who has been in darkness for several hours can see in an exceedingly small amount of light, outdoor tasks must therefore be done with illumination levels that are far below anything that could be considered adequate. When it is realized that the illumination from full moonlight is only about 0.02 footcandles, that on a clear moonless night it is about one-hundredth of this, and that on a cloudless moonless night it is very much less again —of the order of a hundred thousandth of a footcandle—it will be clear why the permitted levels are so low, for in such meager illuminations almost any light becomes conspicuous.

Illuminated signs may still be used, but they must be placed inside of doorways or windows and on ground floors only. The total area of the sign is limited to 3 by 4 ft., and the maximum area of the letters is 144 sq. in. The maximum brightness of the sign is limited to 0.02 footlamberts, and the sign must be inconspicuous at a distance of 100 ft.

Show windows may be illuminated by lamps no bigger than a 25-watt size placed 2½ in. from a 4- by ¼-in. slit covered with tissue paper in a box 6 by 6 by 9 in., painted black on the inside. If more than one box is used in the show windows, they must be at least 10 ft. apart. It takes little imagination to realize how low are the show-window illumination levels when such lighting equipment is used.

As regards street lighting, the regulations stipulate that the general illumination on the road be of the order of 0.0002 footcandle, and at no point can it be more than 0.0004 footcandle (equivalent to the illumination on a clear starlight night). Fixtures must be designed for a mounting height of 10 to 15 ft. and 20 ft., with the maximum candlepower at 75 deg. and with 0 candlepower at 90 deg. Street-lighting units must have no light above the horizontal or directly below the lamp.

General Lighting Design.[1]—The object of all lighting-design calculations is to determine how much of the light produced by the lamps eventually reaches the work plane. This efficiency

[1] A complete discussion of this subject will be found in *Bulletin* LD-6A of the Nela Park Engineering Department entitled "Illumination Design Data" by Ward Harrison and C. E. Weitz.

ratio (lumens that reach the useful working plane to produce footcandles divided by the lumens generated by the lamp) is called the "Coefficient of Utilization."

Well established procedures for lighting design as they have evolved through the past years consist of five principal divisions:

1. Decision as to the footcandle level required.
2. Layout of outlets or arrangement of light sources to provide essentially uniform illumination throughout the room.
3. Provisions for adequate wiring to insure future capacity, convenience switching, and control.
4. Selection of reflecting equipment from the standpoint of efficiency, pleasing design, flexibility, and ease of maintenance.
5. Computation of lamp size necessary to provide the footcandles of illumination desired.

There is nothing mysterious about the light from fluorescent lamps, and a great many of the early misunderstandings about fluorescent lighting would have been explained by the realization that a lumen is a lumen whether it be a "fluorescent lumen," an "incandescent-filament" lumen, or a "mercury lumen." The fundamental concepts of illumination design remain unchanged regardless of the illuminant. The problem is still to determine how many of the lamp lumens will eventually reach the working plane, and the well-established lumen method of illumination design can be applied with equal ease to fluorescent lighting.

In fact, the only way that fluorescent-lighting design differs from filament lighting is in the sequence of steps. In planning a filament-lamp installation, it is customary to locate the outlets for uniformity of illumination and then to use the lamp wattage size that will give the desired footcandle level. Because fluorescent lamps of different wattages are not interchangeable in fixed lampholders and because, generally speaking, different auxiliary equipments are required for the various sizes of fluorescent lamps, the number of fluorescent lamps required to produce the specified illumination level is determined first and then the luminaires are spaced to give a pleasing arrangement.

Spacing Fluorescent Luminaires.—The conventional arrangements of lighting outlets to get uniform illumination with filament lamps have been adequate for a considerable range of footcandles because of the availability of lamp sizes from 15 to 1500 watts with lumen outputs from 150 to 33,000 lumens.

However, with fluorescent lamps, the range is from 15 to 100 watts with lumen outputs from 585 to 4200 lumens (white lamps). Thus, many fluorescent lamps must be used if the higher footcandle levels are to be attained. This means that fixtures will be located on closer spacings.

In planning a general lighting system, the aim is to provide a substantially uniform level of illumination throughout the room. This eliminates spottiness and dark corners and makes

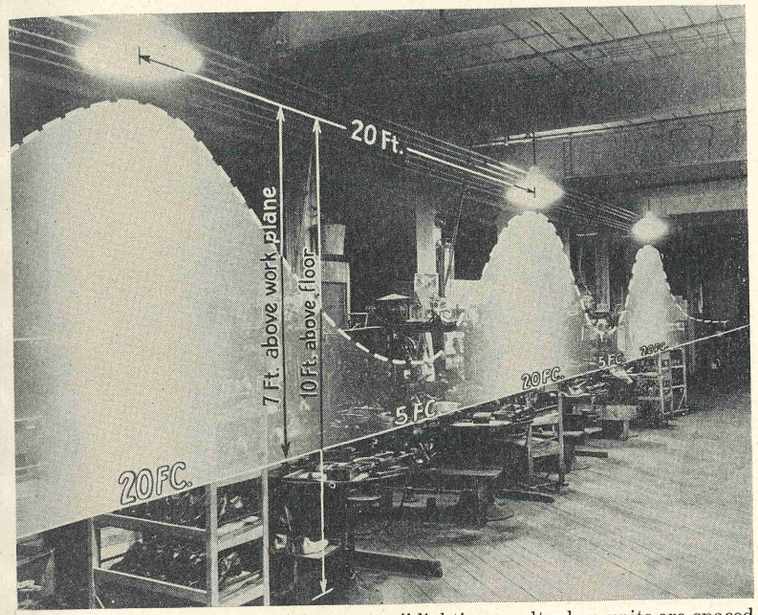


FIG. 127.—Nonuniform or "roller-coaster" lighting result when units are spaced too far apart for their mounting height.

the entire area equally suitable as a work space or for display, sales, or whatever the general purpose may be.

Figure 127 shows what happens when lighting units are spaced too far apart for their mounting height. In this particular case, a 4 to 1 variation in footcandles results, and employees whose work positions are midway between units will be severely penalized as regards seeing conditions in comparison with others whose work is more adequately lighted. Harsh shadows may also result. Figure 128 shows the remedy—mount the units

higher, or if that is impossible, space them closer together as was done in this case.

The spacing for uniform illumination on the work depends on the height of the light source above the surface to be illuminated and upon the distribution characteristics of the luminaire involved. Table 26 shows the recommended luminaire spacings

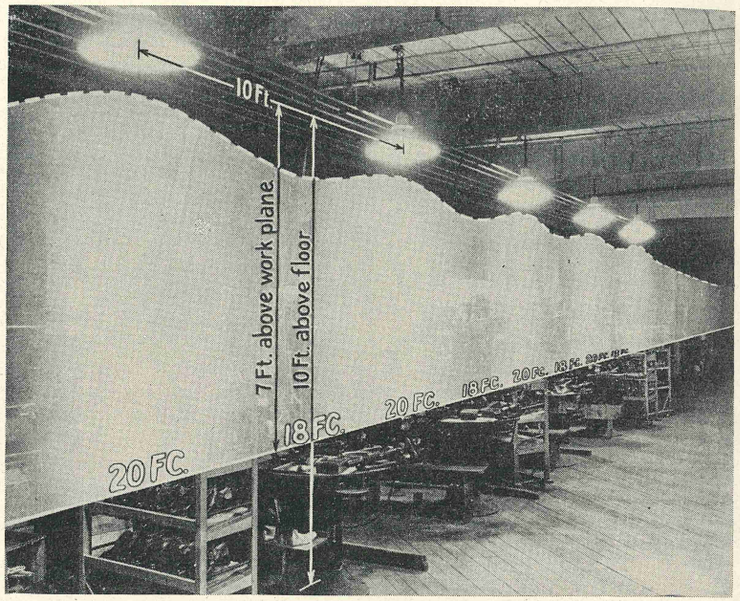


FIG. 128.—Since the units in Fig. 127 could not be raised, the problem was solved by adding a unit between existing outlets.

for various types of distribution. In this table, lighting systems have been grouped into four categories.

1. Indirect.
2. Semi-indirect.
3. Semi-direct.
4. Direct.

Indirect lighting is defined as a system in which nearly all the light from the luminaire goes upward to the ceiling where it is diffusely reflected back to the walls and working plane. The whole ceiling becomes in effect the light source and glare is generally avoided and the shadows are soft. Few totally indirect fluorescent luminaires have made their appearance, although some

splendid indirect-lighting results have been obtained from cove lighting and other built-in systems of this nature.

TABLE 26.—LUMINAIRE SPACINGS
(All dimensions in feet)

Mounting height of luminaire, ceiling height for indirect and semi-indirect luminaires	Type of distribution					
	Indirect or semi-indirect			Direct or semi-direct		
	Maximum spacing between units	Spacing * from walls	Length of suspension	Usual spacing between units	Maximum spacing between units	Spacing * from walls
8	9	3	1–3	7	7½	3
9	9½	3	1½–3	8	8	3
10	10½	3½	2–3	9	9	3½
11	12	3½		10	10½	3½
12	14	4	2½–4	10–12	12	4
13	15	4		10–12	13	4
14	17	5	3–4	10–13	15	5
15	19	5		10–13	17	5
16	21	6	4–5	10–13	19	6
18	23	6		10–20	21	6
20 or more	26	7	4–6	18–24	24	7

* These spacings apply where desks and benches are next to wall; otherwise one-half the spacing between units is satisfactory.

Semi-indirect luminaires are defined as those in which some of the light, usually 5 to 25 per cent, is directed downward but over half the emitted light goes upward.

A semi-direct system consists of one in which the predominant light on the horizontal working surfaces comes directly from the lighting units but where there is also a considerable contribution of the upward light by reflection from the ceiling. This type of distribution will be obtained from bare fluorescent lamps and from a wide variety of fluorescent luminaires in which the down-

TABLE 27.—ROOM INDEX
(Classification of rooms according to their proportions)

For semi-indirect and indirect lighting		Ceiling height, feet											
		9 and 9½	10 to 11½	12 to 13½	14 to 16½	17 to 20	21 to 24	25 to 30	31 to 36	37 to 50			
For direct and semi-direct lighting		Mounting height above floor, feet											
		7 and 7½	8 and 8½	9 and 9½	10 to 11½	12 to 13½	14 to 16½	17 to 20	21 to 24	25 to 30	31 to 36	37 to 50	
Room width, feet	Room length, feet	Room index											
9 (8½–9)	8–10	H	I	J	J								
	10–14	H	I	I	J								
	14–20	G	H	I	J	J							
	20–30	G	G	H	I	J	J						
	30–42	F	G	H	I	J	J	J					
	42–up	E	F	G	H	I	J	J					
10 (9½–10½)	10–14	G	H	I	J	J							
	14–20	G	H	I	J	J	J						
	20–30	F	G	H	I	J	J						
	30–42	F	G	G	H	I	J	J					
	42–60	E	F	G	H	I	J	J					
	60–up	E	F	F	H	H	I	J					
12 (11–12½)	10–14	G	H	I	I	J	J						
	14–20	F	G	H	I	J	J						
	20–30	F	G	G	H	I	J	J					
	30–42	E	F	G	H	I	J	J					
	42–60	E	F	F	G	H	I	J					
	60–up	E	E	F	G	H	I	J					
14 (13–15½)	14–20	F	G	H	H	I	J	J					
	20–30	E	F	G	H	I	J	J					
	30–42	E	F	F	G	H	I	J	J				
	42–60	E	E	F	F	H	I	J	J	J			
	60–90	D	E	E	F	G	H	J	J	J			
	90–up	D	E	E	F	F	G	I	J	J			
17 (16–18½)	14–20	E	F	G	H	I	J	J					
	20–30	E	F	F	G	H	I	J					
	30–42	D	E	F	G	H	H	J	J	J			
	42–60	D	E	E	F	G	G	I	J	J	J		
	60–110	D	E	E	F	G	G	I	J	J	J		
	110–up	C	D	E	E	F	G	H	I	J	J		
20 (19–21½)	20–30	D	E	F	G	H	I	J	J				
	30–42	D	E	E	F	G	H	I	J	J			
	42–60	D	D	E	E	F	G	I	J	J	J		
	60–90	C	D	E	E	F	G	H	J	J	J		
	90–140	C	D	D	E	F	F	H	I	J	J		
	140–up	C	D	D	E	F	F	H	I	I	J	J	
24 (22–26)	20–30	D	E	E	F	G	H	I	J	J			
	30–42	C	D	E	E	G	G	I	J	J			
	42–60	C	D	D	E	F	G	I	J	J	J		
	60–90	C	D	D	E	F	F	H	J	J	J		
	90–140	C	C	D	E	E	F	G	I	J	J		
	140–up	C	C	D	E	E	F	G	H	I	J	J	

TABLE 27.—ROOM INDEX.—(*Continued*)
(Classification of rooms according to their proportions)

For semi-indirect and indirect lighting		Ceiling height, feet											
		9 and 9½	10 to 11½	12 to 13½	14 to 16½	17 to 20	21 to 24	25 to 30	31 to 36	37 to 50			
For direct and semi-direct lighting		Mounting height above floor, feet											
		7 and 7½	8 and 8½	9 and 9½	10 to 11½	12 to 13½	14 to 16½	17 to 20	21 to 24	25 to 30	31 to 36	37 to 50	
Room width, feet	Room length, feet	Room index											
30 (27–33)	30–42	C	D	D	E	F	G	H	I	J	J		
	42–60	C	D	D	D	F	F	H	H	I	J	J	
	60–90	B	C	C	D	E	E	G	H	I	J	J	J
	90–140	B	C	C	D	E	E	F	G	I	I	J	J
	140–180	B	C	C	D	E	E	F	G	H	I	J	J
	180–up	B	C	C	D	E	E	F	G	H	I	J	J
36 (34–39)	30–42	B	C	D	E	F	F	H	I	I	J		
	42–60	B	C	C	D	E	F	G	H	I	J	J	
	60–90	A	C	C	C	E	E	F	H	H	J	J	J
	90–140	A	B	C	C	D	E	F	G	H	I	J	J
	140–200	A	B	C	C	D	E	F	F	G	H	I	I
	200–up	A	B	C	C	D	E	F	F	G	H	I	I
42 (40–45)	42–60	A	B	C	C	E	F	G	H	I	I	J	
	60–90	A	B	B	C	D	E	F	G	H	I	J	J
	90–140	A	B	B	C	D	D	E	F	G	H	J	J
	140–200	A	A	B	C	D	D	E	F	G	H	I	I
	200–up	A	A	B	C	D	D	E	F	F	G	I	I
50 (46–55)	42–60	A	A	B	C	D	E	F	G	H	I	J	
	60–90	A	A	B	C	C	D	F	F	G	H	J	J
	90–140	A	A	A	C	C	D	E	F	F	G	I	I
	140–200	A	A	A	C	C	D	E	E	F	G	I	I
	200–up	A	A	A	C	C	D	E	E	F	G	H	H
60 (56–67)	60–90	A	A	A	B	C	D	E	F	G	H	I	
	90–140	A	A	A	B	C	C	D	E	F	G	H	H
	140–200	A	A	A	B	C	C	D	E	E	F	H	H
	200–up	A	A	A	B	C	C	D	E	E	F	H	H
75 (68–90)	60–90	A	A	A	A	B	C	D	E	F	G	I	
	90–140	A	A	A	A	B	C	D	E	F	F	H	G
	140–200	A	A	A	A	B	B	C	D	E	F	G	G
	200–up	A	A	A	A	B	B	C	D	E	F	G	G
90 or more	60–90	A	A	A	A	B	C	D	E	F	G	H	
	90–140	A	A	A	A	A	B	C	D	E	F	G	G
	140–200	A	A	A	A	A	B	C	D	E	F	G	F
	200–up	A	A	A	A	A	B	C	D	D	E	F	F

ward component predominates but where the upward light is appreciable.

A direct-lighting fixture is one in which the light is directed essentially downward. In this category are RLM fluorescent luminaires, troffers, and most industrial-type fluorescent reflectors.

Although these definitions of indirect, semi-indirect, semi-direct, and direct-lighting luminaires seem rather general, there need be no confusion as to the proper classification of a fluorescent fixture. If, say, 90 to 100 per cent of the luminaire output (not the percentage of lamp lumens) is upward, it is an indirect unit. When 60 to 90 per cent of the luminaire output is upward and the rest downward, the unit would be classified as semi-indirect. If, say, 40 to 90 per cent of the luminaire output is downward, it is a direct-lighting unit.

Fluorescent luminaires of either the semi-indirect or semi-direct type may be called "direct-indirect" units if they are so designed as to present low brightnesses in the direct-glare zone. This simply means that the horizontal candlepower is quite low.

It will be seen from Table 26 that, in general, spacing distances which do not substantially exceed the mounting height will result in reasonably uniform illumination.

Room Proportion and Room Index.—In general, large rooms use light more efficiently than do small rooms because there is less wall area to absorb light in proportion to the floor space. For the same reason, rooms with high ceilings are less efficiently lighted than low-ceilinged rooms, other dimensions remaining the same. Table 27 shows a classification of room proportions in 10 groups indicated by letters *A* to *J*. In early publications the Room Index was shown numerically, and for those who have become accustomed to that system, Table 28 shows the numerical room ratios to which the Room Indexes correspond.

TABLE 28.—ROOM INDEX—ROOM RATIO EQUIVALENTS

Room Ratio	Equivalent Room Index
0.6	*J*
0.8	*I*
1.0	*H*
1.25	*G*
1.5	*F*
2.0	*E*
2.5	*D*
3.0	*C*
4.0	*B*
5.0	*A*

It should be noted that the Room Index is simply a classification of a room according to the proportion of width, length, and height. Two interiors whose dimensions have the same proportions will have the same Room Index. For example, a room 20 ft. wide, 25 ft. long, and 10 ft. high has the same Room Index as a room 40 ft. wide, 50 ft. long, and 20 ft. high (each of the latter dimensions being twice the former). Hence, for large rooms having dimensions greater than those shown in Table 27, simply divide each dimension by a constant factor and use the index determined for the proportionately smaller room. The Coefficient of Utilization in extra-large interiors is discussed later in this chapter.

Coefficients of Utilization.—As previously mentioned, the Coefficient of Utilization is the ratio of the lumens that reach the work plane[1] (and are useful in producing footcandles) to the lumens generated by the lamp. It is, therefore, the illumination-efficiency factor. Coefficients of Utilization are computed from the candlepower-distribution curves in accordance with basic experimental data which have been available to the lighting industry for many years.[2]

Coefficients of Utilization data are given for several types of fluorescent luminaires in Table 29. Although it is obviously impossible to give coefficients for, or to classify, the hundreds of different fluorescent equipments listed in equipment manufacturers' catalogues, the selection given covers many of the fixture types in common use.

A study of these Coefficients of Utilization is of extreme value, since the various data illustrate the effect of room proportions, ceiling and wall reflection conditions, etc. It will be quite evident, for example, that a narrow or concentrating distribution will direct the light more strongly downward (keeping less light from striking the walls and ceiling) than will a broad distribution. In the former case, the influence of the size of the room or the color of walls and ceiling on the utilization is much less than the latter case where a large proportion of light strikes the walls and ceilings from which only a portion is reflected to work surfaces. Note also that the influence of the interior finish (the reflectivity of ceiling and walls) is less important with direct

[1] Unless otherwise specified, the work plane is assumed to be a horizontal plane 30 in. above the floor.

[2] WARD HARRISON and EARL A. ANDERSON, "Coefficients of Utilization," *Transactions of the Illuminating Engineering Society*, vol. 15, No. 2, Mar. 20, 1920.

TABLE 29[1]

Fluorescent luminaires	Form of distribution curve	Ceiling	75%			50%			30%	
		Walls	50%	30%	10%	50%	30%	10%	30%	10%
		Room index	Coefficients of utilization							
Specular Reflector Unit		*J*	.40	.38	.36	.39	.38	.36	.38	.36
		I	.48	.46	.46	.47	.46	.46	.45	.43
		H	.51	.51	.50	.50	.50	.49	.50	.48
		G	.55	.54	.54	.54	.52	.52	.52	.51
		F	.58	.56	.55	.55	.55	.54	.55	.53
		E	.60	.59	.58	.59	.58	.57	.57	.56
		D	.64	.61	.60	.62	.60	.60	.60	.59
		C	.65	.63	.61	.63	.62	.60	.60	.60
M.F. = 0.75	0% up 70% down	*B*	.65	.64	.63	.64	.62	.62	.62	.61
		A	.66	.65	.64	.64	.63	.62	.62	.62
RLM Fluorescent Unit*		*J*	.37	.32	.28	.37	.32	.28	.31	.28
		I	.46	.41	.38	.45	.40	.37	.40	.37
		H	.50	.46	.43	.49	.46	.43	.45	.43
		G	.54	.50	.47	.53	.50	.47	.48	.47
		F	.58	.54	.50	.56	.52	.50	.52	.50
		E	.62	.59	.56	.61	.58	.56	.57	.56
		D	.67	.64	.60	.65	.63	.60	.62	.60
		C	.69	.66	.63	.67	.64	.63	.64	.62
M.F. = 0.75	0% up 79% down	*B*	.72	.69	.67	.70	.68	.66	.67	.65
		A	.74	.71	.69	.72	.69	.68	.68	.67
RF Fluorescent Unit†		*J*	.36	.30	.27	.35	.30	.27	.30	.27
		I	.44	.40	.36	.43	.39	.36	.39	.36
		H	.48	.44	.41	.47	.44	.41	.43	.41
		G	.52	.48	.45	.51	.48	.45	.46	.45
		F	.55	.51	.48	.53	.50	.48	.49	.48
		E	.60	.57	.54	.58	.55	.53	.55	.53
		D	.64	.61	.58	.62	.60	.58	.59	.58
		C	.66	.63	.60	.64	.62	.60	.61	.59
M.F. = 0.75	0% up 76% down	*B*	.69	.66	.64	.67	.64	.63	.64	.62
		A	.70	.68	.66	.68	.66	.64	.65	.64
Recessed Troffer		*J*	.32	.28	.25	.32	.28	.25	.27	.25
		I	.40	.36	.34	.39	.35	.33	.35	.33
		H	.43	.39	.37	.42	.39	.37	.39	.37
		G	.46	.43	.41	.45	.43	.41	.43	.41
		F	.48	.45	.43	.47	.45	.43	.45	.43
		E	.52	.50	.48	.51	.49	.47	.49	.47
		D	.56	.54	.52	.55	.53	.51	.53	.51
		C	.57	.55	.53	.56	.54	.52	.54	.52
M.F. = 0.75	0% up 65% down	*B*	.60	.58	.56	.59	.57	.55	.57	.55
		A	.61	.59	.57	.60	.58	.57	.58	.56
Shielded V Unit‡		*J*	.28	.25	.23	.27	.25	.23	.25	.23
		I	.34	.31	.30	.33	.30	.29	.30	.29
		H	.37	.35	.33	.36	.34	.32	.34	.32
		G	.40	.38	.36	.38	.36	.35	.36	.34
		F	.43	.40	.38	.40	.38	.37	.38	.36
		E	.45	.43	.41	.44	.42	.40	.41	.39
		D	.49	.45	.43	.46	.44	.42	.43	.42
		C	.50	.47	.44	.48	.44	.43	.44	.43
M.F. = 0.70	6% up 56% down	*B*	.52	.49	.47	.50	.47	.46	.46	.45
		A	.53	.51	.49	.51	.48	.47	.47	.46
100-watt Shielded V Unit		*J*	.28	.24	.22	.26	.23	.21	.23	.21
		I	.34	.31	.29	.32	.29	.27	.28	.26
		H	.37	.34	.32	.35	.32	.30	.31	.29
		G	.41	.38	.35	.38	.35	.33	.33	.31
		F	.44	.40	.37	.40	.37	.35	.35	.33
		E	.47	.44	.41	.43	.41	.38	.38	.36
		D	.51	.47	.44	.46	.43	.41	.41	.39
		C	.53	.49	.46	.48	.45	.43	.42	.40
M.F. = 0.70	22% up 50% down	*B*	.55	.52	.49	.50	.47	.45	.44	.43
		A	.57	.54	.51	.52	.49	.47	.45	.44

[1] Many of these data are taken from Folder D, "Essential Data for General Lighting Design," published by the Nela Park Engineering Department, General Electric Company.
* Output and coefficients are slightly *lower* for 100-watt RLM units.
† Output and coefficients are slightly *higher* for standard single-lamp RF units.
‡ Coefficients are about 20 per cent *higher* for unbaffled units.

TABLE 29.[1]—(*Continued*)

Fluorescent luminaires	Form of distribution curve	Ceiling	75%			50%			30%	
		Walls	50%	30%	10%	50%	30%	10%	30%	10%
		Room index	Coefficients of utilization							
Flat Reflector with Plastic Louvers		*J*	.33	.29	.27	.32	.29	.27	.29	.26
		I	.40	.37	.35	.38	.35	.34	.35	.33
		H	.43	.41	.39	.42	.39	.38	.39	.37
		G	.47	.44	.42	.45	.43	.41	.42	.40
		F	.50	.47	.44	.47	.45	.43	.45	.43
		E	.54	.51	.48	.51	.49	.47	.48	.46
		D	.57	.54	.51	.54	.52	.50	.51	.49
		C	.59	.56	.53	.56	.54	.51	.52	.51
M.F. = 0.70	8% up 65% down	*B*	.61	.58	.56	.58	.55	.54	.54	.53
		A	.63	.60	.58	.60	.57	.55	.55	.54
Metal Louvers—Plastic Sides		*J*	.27	.24	.23	.25	.23	.22	.23	.21
		I	.33	.30	.29	.31	.29	.28	.28	.26
		H	.36	.34	.32	.34	.32	.31	.31	.29
		G	.39	.37	.35	.36	.34	.33	.33	.32
		F	.41	.39	.37	.38	.36	.35	.35	.34
		E	.44	.42	.40	.41	.39	.38	.37	.36
		D	.47	.44	.42	.43	.42	.40	.39	.38
		C	.48	.46	.43	.45	.43	.41	.40	.39
M.F. = 0.70	16% up 46% down	*B*	.50	.48	.46	.46	.44	.43	.42	.41
		A	.51	.49	.48	.47	.46	.44	.43	.42
Glass Louvers, White Reflectors		*J*	.33	.28	.26	.32	.28	.25	.26	.24
		I	.41	.36	.34	.39	.35	.32	.34	.32
		H	.45	.41	.38	.43	.40	.37	.38	.36
		G	.49	.45	.42	.46	.43	.40	.41	.39
		F	.52	.48	.45	.49	.46	.43	.44	.42
		E	.57	.53	.49	.53	.50	.47	.48	.46
		D	.61	.57	.53	.57	.54	.52	.52	.50
		C	.63	.59	.56	.59	.56	.54	.54	.52
M.F. = 0.70	17% up 65% down	*B*	.66	.63	.60	.62	.59	.57	.56	.55
		A	.68	.65	.62	.64	.61	.59	.58	.56
Half Cylinder Shielded		*J*	.22	.18	.15	.20	.17	.14	.15	.14
		I	.27	.23	.20	.25	.21	.19	.20	.18
		H	.30	.26	.24	.28	.25	.22	.23	.21
		G	.33	.30	.27	.30	.27	.25	.25	.23
		F	.36	.32	.29	.32	.29	.27	.27	.25
		E	.40	.36	.33	.36	.33	.30	.30	.28
		D	.43	.39	.36	.38	.36	.33	.33	.31
		C	.45	.41	.38	.40	.37	.35	.34	.33
M.F. = 0.65	23% up 43% down	*B*	.48	.45	.42	.43	.40	.38	.37	.35
		A	.50	.46	.44	.45	.42	.40	.38	.37
Half Cylinder Unshielded		*J*	.30	.24	.21	.28	.23	.20	.22	.19
		I	.37	.32	.28	.35	.30	.26	.28	.26
		H	.42	.36	.33	.38	.34	.31	.32	.29
		G	.46	.41	.37	.42	.38	.35	.35	.31
		F	.50	.44	.40	.45	.41	.37	.38	.35
		E	.55	.50	.45	.50	.46	.42	.42	.40
		D	.59	.54	.49	.54	.50	.46	.46	.44
		C	.62	.57	.52	.56	.52	.49	.49	.46
M.F. = 0.75	28% up 58% down	*B*	.66	.62	.57	.60	.55	.53	.52	.50
		A	.69	.64	.60	.62	.56	.55	.53	.52
Wedge Unit, Glass		*J*	.23	.19	.16	.21	.17	.15	.16	.14
		I	.28	.24	.22	.26	.22	.20	.21	.19
		H	.31	.27	.25	.29	.25	.23	.23	.21
		G	.35	.31	.28	.31	.28	.26	.26	.24
		F	.38	.34	.30	.34	.30	.28	.28	.26
		E	.42	.38	.34	.37	.34	.31	.31	.29
		D	.45	.41	.37	.40	.37	.34	.34	.32
		C	.48	.43	.40	.42	.39	.36	.35	.33
M.F. = 0.65	29% up 43% down	*B*	.51	.47	.44	.45	.41	.39	.38	.36
		A	.53	.49	.46	.47	.43	.41	.39	.38

[1] Many of these data are taken from Folder D, "Essential Data for General Lighting Design," published by the Nela Park Engineering Department, General Electric Company.

TABLE 29.[1]—(*Continued*)

Fluorescent luminaires	Form of distribution curve	Ceiling	75%			50%			30%	
		Walls	50%	30%	10%	50%	30%	10%	30%	10%
		Room index	Coefficients of utilization							
Louvered-bottom Wedge		*J*	.24	.20	.18	.22	.19	.16	.17	.16
		I	.30	.26	.24	.27	.24	.22	.22	.21
		H	.33	.30	.27	.30	.27	.25	.25	.23
		G	.37	.33	.30	.33	.30	.28	.27	.26
		F	.40	.36	.32	.35	.31	.30	.30	.28
		E	.44	.40	.37	.39	.36	.32	.33	.31
		D	.47	.43	.40	.42	.39	.37	.36	.34
		C	.49	.46	.42	.44	.41	.39	.37	.35
		B	.52	.49	.46	.46	.43	.42	.39	.38
M.F. = 0.70	29% up 43% down	*A*	.54	.51	.48	.48	.45	.43	.41	.39
Elliptical Specular Reflectors		*J*	.34	.31	.29	.31	.29	.28	.29	.26
		I	.41	.38	.37	.38	.36	.35	.34	.32
		H	.45	.43	.41	.41	.39	.38	.37	.35
		G	.49	.46	.45	.44	.42	.41	.39	.38
		F	.52	.49	.47	.46	.44	.43	.41	.40
		E	.55	.52	.51	.49	.48	.46	.44	.42
		D	.59	.55	.53	.52	.50	.49	.46	.45
		C	.60	.58	.55	.54	.52	.50	.47	.46
		B	.62	.60	.58	.55	.53	.52	.48	.47
M.F. = 0.70	33% up 48% down	*A*	.64	.62	.60	.57	.55	.53	.49	.48
Direct-indirect, Deep Louvers		*J*	.23	.20	.18	.19	.17	.16	.16	.14
		I	.27	.25	.23	.23	.21	.20	.19	.18
		H	.30	.28	.26	.26	.24	.23	.21	.20
		G	.34	.31	.29	.29	.26	.25	.23	.22
		F	.36	.33	.31	.30	.28	.27	.24	.23
		E	.39	.37	.34	.33	.31	.29	.26	.25
		D	.42	.39	.37	.35	.33	.31	.27	.27
		C	.44	.41	.39	.36	.34	.33	.28	.27
		B	.47	.44	.42	.38	.36	.35	.30	.29
M.F. = 0.70	45% up 25% down	*A*	.48	.46	.44	.39	.37	.36	.31	.30
Direct-indirect, Shallow Louvers		*J*	.24	.19	.16	.23	.20	.16	.18	.16
		I	.30	.26	.22	.28	.24	.21	.24	.21
		H	.33	.28	.26	.32	.28	.25	.27	.24
		G	.37	.33	.29	.34	.31	.28	.29	.27
		F	.40	.36	.32	.37	.33	.30	.32	.29
		E	.44	.40	.36	.41	.38	.34	.35	.33
		D	.47	.43	.39	.44	.41	.38	.39	.37
		C	.50	.46	.42	.46	.43	.40	.41	.38
		B	.54	.50	.46	.50	.46	.44	.44	.42
M.F. = 0.70	35% up 42% down	*A*	.56	.52	.48	.51	.48	.45	.45	.44
Diffracting Bottom, Sides*		*J*	.30	.27	.25	.27	.25	.24	.25	.22
		I	.36	.33	.32	.33	.31	.30	.30	.28
		H	.39	.37	.36	.36	.34	.33	.33	.31
		G	.43	.41	.39	.39	.37	.36	.35	.33
		F	.46	.43	.41	.41	.39	.38	.37	.35
		E	.49	.46	.44	.44	.42	.40	.39	.38
		D	.52	.49	.47	.47	.45	.43	.41	.40
		C	.54	.51	.48	.48	.46	.44	.42	.41
		B	.56	.53	.51	.50	.48	.47	.44	.43
M.F. = 0.70	27% up 46% down	*A*	.57	.55	.53	.51	.49	.48	.45	.44
Enclosed Channel		*J*	.28	.24	.22	.25	.23	.21	.21	.19
		I	.34	.31	.29	.31	.28	.27	.26	.25
		H	.38	.35	.33	.34	.32	.30	.29	.28
		G	.42	.39	.36	.37	.35	.33	.32	.31
		F	.44	.41	.38	.39	.37	.35	.34	.32
		E	.48	.45	.42	.43	.40	.38	.36	.35
		D	.52	.48	.46	.46	.43	.41	.39	.38
		C	.54	.51	.48	.47	.45	.43	.40	.39
		B	.57	.54	.52	.49	.47	.46	.42	.41
M.F. = 0.70	18% up 54% down	*A*	.58	.55	.53	.51	.49	.47	.43	.42

[1] Many of these data are taken from Folder D, "Essential Data for General Lighting Design," published by the Nela Park Engineering Department General Electric Company.
* Coefficients are very similar for ceiling-mounted units of this type.

reflectors, becoming increasingly influential with semi-direct lighting and a major factor in lighting efficiency with semi-indirect and indirect lighting.

The maximum wall-reflection factor given in the Coefficient of Utilization tables is 50 per cent. Even though very light walls having higher reflection factors are sometimes used, the net value seldom exceeds 50 per cent when allowance is made for wall furnishings and door and window openings.

Coefficients of Utilization are extremely useful since they bring together all the factors that affect the initial efficiency of the lighting system. However, it must be remembered that the Coefficients of Utilization given here are calculated for the percentage of light output and distribution shown. The fixtures illustrated are typical and are not intended to represent the specific performance of any manufacturer's product. A fixture having a candlepower-distribution curve similar in shape to one of the distribution curves shown, but with a slightly different output, may be considered as having coefficients raised or lowered in proportion to the actual light output. Thus, the selection of coefficients to be used with an actual fixture should be based on the candlepower-distribution curve and the luminaire output—several luminaires may look about the same but differ considerably in these respects.

For example, if a half-cylinder plastic type of unit similar to that shown in Table 29 had an output of say 60 per cent (as disclosed by photometric data or by the manufacturer's published output) with a distribution curve similar in type and shape to the curve shown, the coefficients for the specific unit under consideration could be obtained by multiplying the values from Table 29 for that type of fixture by the ratio 60/66. Once the effect of room proportions, room finishes, output, distribution characteristics, etc., on the Coefficients of Utilization are thoroughly understood, the lighting man can make acceptable allowance from the range of data given here for any departures which the actual photometric data on a specific luminaire may disclose.

Maintenance Factor.—An allowance must always be made for depreciation of lamps, reflectors, and reflecting surfaces (ceiling, walls, etc.), so that the desired footcandle level will be maintained in service. Fluorescent lamps themselves depreciate to about 80 per cent of their rated light output by the end of their rated

life, and the inevitable film of dust that collects quickly on reflecting surfaces accounts for still more depreciation even when a reasonable cleaning schedule is followed. The average illumination maintained in service will, under average conditions, be of the order of about 70 per cent of the initial value, or 0.70 when expressed as a maintenance factor. Of course, these factors depend on the type of luminaire and the local conditions as regard smoke, dust, dirt, etc. In some instances, particularly with direct-lighting equipment, there is little reflecting surface exposed for falling dust to settle on, and the maintenance factor may be higher than 70 per cent. However, direct-indirect equipments or luminaires exposing considerable lamp or reflector area to falling dust and dirt may have maintenance factors lower than 70 per cent.

The maintenance factors given in Table 29 apply for average conditions as regard dust and dirt in the atmosphere and can be used with assurance provided a reasonable cleaning schedule is followed.[1]

The Basic Formula.—Since the Coefficient of Utilization indicates the percentage of the lumens generated by the lamp which reach the work surface and the maintenance factor represents the proportion of the initial footcandle level which will be provided on the average in service

$$\begin{pmatrix}\text{Lumens reaching}\\ \text{work plane}\end{pmatrix} = \begin{pmatrix}\text{total lamp}\\ \text{lumens}\end{pmatrix}\begin{pmatrix}\text{coefficient of}\\ \text{utilization}\end{pmatrix}\begin{pmatrix}\text{maintenance}\\ \text{factor}\end{pmatrix}$$

Since the average footcandle level is equal to the lumens reaching the working plane divided by the area, we can divide both sides of the preceding equation by the total area and the result is

$$\text{Footcandles} = \frac{\begin{pmatrix}\text{total lamp}\\ \text{lumens}\end{pmatrix}\begin{pmatrix}\text{coefficient of}\\ \text{utilization}\end{pmatrix}\begin{pmatrix}\text{maintenance}\\ \text{factor}\end{pmatrix}}{\text{area in square feet}}$$

Or, on a "per lamp" basis,

$$\text{Footcandles} = \frac{\begin{pmatrix}\text{lumens per}\\ \text{lamp}\end{pmatrix}\begin{pmatrix}\text{coefficient of}\\ \text{utilization}\end{pmatrix}\begin{pmatrix}\text{maintenance}\\ \text{factor}\end{pmatrix}}{\text{area in square feet per lamp}}$$

[1] See Maintenance in Chap. VI.

As mentioned earlier, the procedure in fluorescent-illumination design is somewhat different than in filament-lamp design because fluorescent luminaires can be used with only the size and wattage of fluorescent lamps for which they were designed. Therefore, when the desired footcandle level and the fluorescent luminaires have been selected, the number of luminaires required is often determined before the actual layout of fixtures is made. Thus a useful formula in fluorescent design is

$$\begin{pmatrix}\text{Square feet}\\ \text{per luminaire}\end{pmatrix} = \frac{\begin{pmatrix}\text{lamp lumens}\\ \text{per luminaire}\end{pmatrix}\begin{pmatrix}\text{coefficient of}\\ \text{utilization}\end{pmatrix}\begin{pmatrix}\text{maintenance}\\ \text{factor}\end{pmatrix}}{\text{footcandle level desired}}$$

in which

$$\begin{pmatrix}\text{Lamp lumens}\\ \text{per luminaire}\end{pmatrix} = \begin{pmatrix}\text{lumens per}\\ \text{lamp}\end{pmatrix}\begin{pmatrix}\text{number of lamps}\\ \text{per luminaire}\end{pmatrix}$$

The total square feet to be lighted is divided by the square feet per luminaire value obtained by the preceding formula to determine the number of luminaires that will be needed. The luminaires can then be placed at existing outlets or located to give uniform lighting and a pleasing arrangement.

By using such a formula, the footcandle levels can be calculated for the specific conditions at hand. As a convenience and to serve as a check for specific calculations, Table 30 gives the computed footcandle level for various Coefficients of Utilization and for different areas per 40-watt white fluorescent lamp. This table is based on the present rated output of 2100 lumens for this lamp and on a maintenance factor of 0.70. The footcandle values would be about 85 per cent of those given in Table 30 if the 40-watt daylight lamps were employed, or about 70 per cent for the 40-watt soft-white lamp. The area in square feet per lamp is determined by dividing the total floor area to be lighted by the total number of lamps (not fixtures) to be used. Values are given to the nearest footcandle, since tables of this nature are more frequently used for arithmetical checking than for accurate predictions of illumination levels.

Designed and Measured Footcandles.—The "lumen method" of illumination design employing Coefficients of Utilization applies only as far as design for uniform illumination over a given area is concerned. This method, therefore, cannot be

expected to give accurate results unless luminaires are spaced to give reasonably uniform lighting over the entire working plane.

TABLE 30.—COMPUTED VALUES OF ILLUMINATION, FOOTCANDLES IN SERVICE
(Maintenance factor of 0.70 used)

Area in square feet per 40-watt white fluorescent lamp*	Coefficient of Utilization											
	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70
5	44	59	74	88	103	118	132	147	162	177	191	206
6	37	49	61	74	86	98	110	123	135	147	159	172
7	32	42	53	63	74	84	95	105	116	126	137	147
8	28	37	46	55	65	74	83	92	101	110	120	129
9	25	33	41	49	57	65	74	82	90	98	106	114
10	22	29	37	44	52	59	66	74	81	88	96	103
12	18	25	31	37	43	49	55	61	67	74	80	86
14	16	21	26	32	37	42	47	53	58	63	68	74
16	14	18	23	28	32	37	41	46	51	55	60	64
18	12	16	20	25	29	33	37	41	45	49	53	57
20	11	15	18	22	26	29	33	37	40	44	48	52
22	10	13	17	20	23	27	30	33	37	40	43	47
24	9	12	15	18	21	25	28	31	34	37	40	43

* These values are about 15 per cent lower for 40-watt daylight lamps, about 30 per cent lower for 40-watt soft-white lamps.

The footcandle level calculated by the lumen method is an absolute average based on the total number of lumens reaching the work surface divided by that area. However, absolute uniformity seldom is realized in actual installations, and practical considerations in layout and the variable influence of walls and other extraneous surfaces that intercept and reflect light affect the final result. Figure 129 shows a typical business office lighted with six direct-indirect luminaires each employing four 40-watt white-lamps (one lamp per each 11 sq. ft. approximately). The lower curve shows the footcandle variation through the room.[1] Notice that at the center of the desk, directly under one of the units, the footcandle level is 60 and along the wall and between luminaires it has dropped to 35.

Although the variation from average footcandles will be less than shown in Fig. 129 for those larger rooms where the walls

[1] The dots and *X*'s indicate brightness readings in footlamberts.

have less of an influence, it should be remembered that there is always some nonuniformity throughout the working area. It is inaccurate, therefore, to determine the footcandle level in an installation by taking a single footcandle-meter reading. A measurement taken at the center of the room, directly under one luminaire or at some other point where the footcandle level is highest, would not necessarily represent the average footcandle level throughout the area.

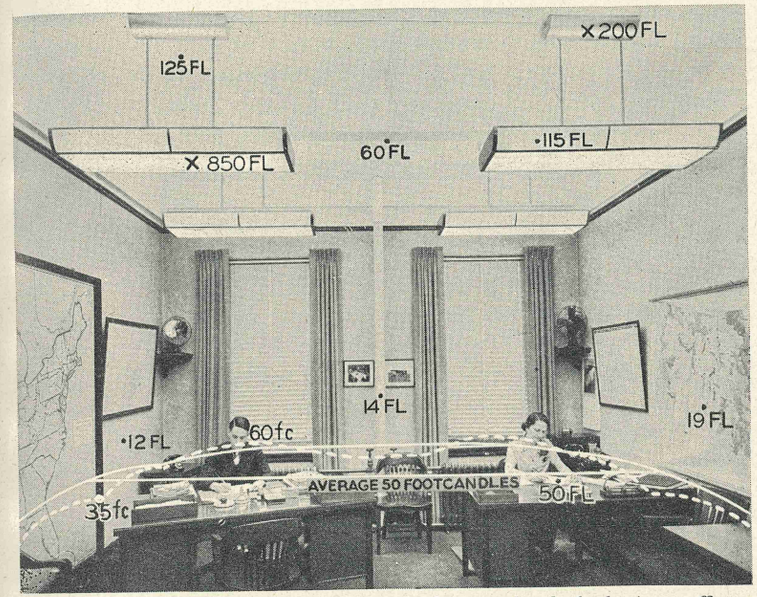


FIG. 129.—Typical footcandle variation at the work level of a business office.

Coefficients of Utilization in Large Areas.—It will be noted by inspecting the Room Index table that the index for a direct-lighting system in which the mounting height is say 7 or 7½ ft. is *A* whether the room is 36 ft. wide and 60 to 90 ft. long or whether the room is 90 or more feet wide and 200 or more feet long. Obviously, the utilization will be higher for the latter condition because less wall area is presented to absorb some light and therefore a greater proportion of the luminaire output will be useful in producing footcandles. This effect has little commercial significance except in those few cases where tremendously large interiors are involved as in certain industrial interiors especially

of the size sometimes encountered in defense plants of current construction. It was mentioned under the discussion of Room Index that the dimensions could be scaled down by a common denominator so that they fall within the limits of the Room Index table, but this is practical only when the ceiling heights under consideration are proportionately high.

For those very few cases involving exceedingly large areas and where more accurate coefficients must be determined, it is possible to calculate how much the utilization for an *A* room condition should be increased. However, such a procedure is beyond the scope of this manual and in some respects implies an accuracy actually exceeding in most cases that of the footcandle-measuring instrument with which the illumination level is checked, to say nothing of the vastly greater variations and assumptions made of wall and ceiling reflections or even the maintenance factors on which such calculations are predicated. Actually, the lighting engineer need have little fear in using the highest Coefficient of Utilization normally published for the unit at hand where tremendously large areas are involved. For, though an increase in the coefficient is theoretically justified in such cases, it is doubtful that the few per cent thus calculated would be apparent in practical footcandle-meter measurements and, even if measured, of little practical significance.

Layout Suggestions.—Whereas filament lamps offer greater flexibility in wattage sizes, the fluorescent lamp, by virtue of its tubular form, suggests new layout and installation methods, *i.e.*, continuous rows of luminaires, the use of "troffer" systems, cornice-type units, etc. There are, however, several typical layout plans for use where the lighting system must conform with a certain structural design.

Figure 130 illustrates four such typical layouts. Sketch *A* shows the use of four units per bay, the common arrangement for the square bay of the usual dimensions. *B* shows the four-two system which is equivalent to three units per bay and is alternative to four per bay where the spacing allows. Sketch *C* shows the use of two units per bay, usually applicable to narrow bays where the width is less than two-thirds the length. *D* shows the use of a single unit per bay, satisfactory only where the bay size is no greater than the maximum allowable spacing—an unusual condition except in high-ceilinged rooms. In many cases, the

principle of these arrangements can be followed, though frequently more fluorescent units will be required to get the desired footcandle levels.

Generally speaking, fluorescent luminaires are located to give a symmetrical appearance and reasonably uniform illumination throughout the working area. This sometimes means that a spacing smaller than that indicated in Table 26 must be employed in order to obtain a symmetrical layout in accordance with the arrangement of bays, partitions, or other architectural features. These closer spacings will tend to improve uniformity, as well as to reduce shadows at any given point.

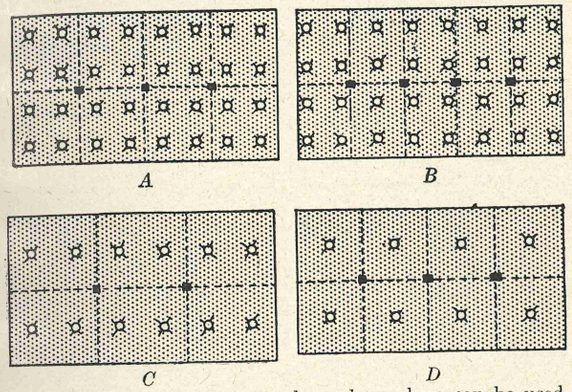


FIG. 130.—Typical layouts of units such as shown here can be used when the lumen output per unit is sufficient to produce the footcandle levels desired.

Built-in Architectural Elements.—The extended tubular shape of fluorescent lamps makes them especially appropriate for built-in architectural elements, the variety of which is limited only by the ingenuity of the lighting engineer. Figure 131 shows four typical types of built-in architectural elements.

The "troffer" type of fluorescent lighting is an especially popular one, for it permits the economical attainment of both light, sound, and air conditioning. This refers, of course, to the common practice of using acoustical ceiling materials between the troffers. The other types of built-in architectural elements shown in Fig. 131 are more of the custom-built variety and require more individual and intimate treatment of the different areas. Their layouts are concerned principally with architectural harmony and appearance. However, such elements should be so arranged and

spaced as to produce appropriately uniform lighting for the visual requirement of the interior. Like conventional units, the spacing between individual elements should not exceed the values given in the spacing table if substantial uniformity is to be obtained.

Simplified Design Methods.—Because many people now interested in planning and selling fluorescent installations are relatively inexperienced in making lighting-design calculations,

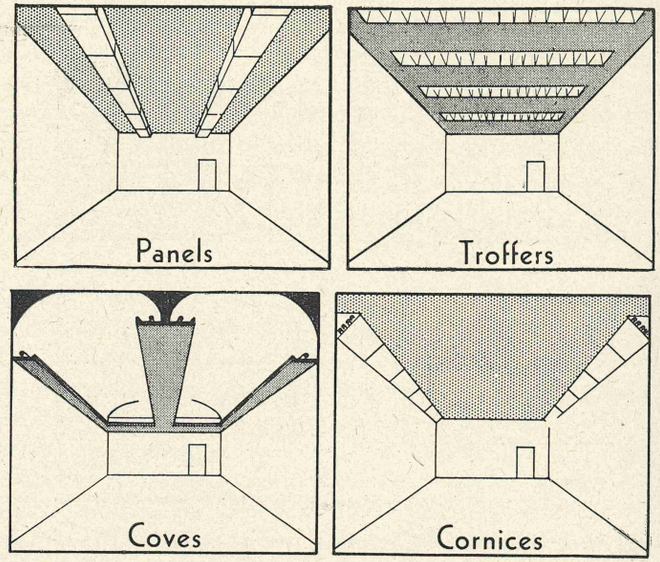
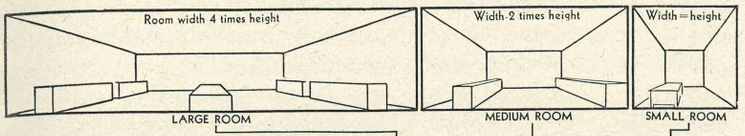


FIG. 131.—Four types of typical built-in architectural elements.

many simplified methods have been introduced. Among the popular and most useful of these simplified methods are the "square feet per lamp," or "square feet per luminaire," data for specific luminaires or for general luminaire types. Figure 132 shows such a tabulation for several general types of fluorescent luminaires, the data being based on the maintenance of 50 footcandles in service, using 40-watt white fluorescent lamps. In this and in many similar tabulations, the large room represents a *B* Room Index and is a good approximation for interiors having an *A*, *B*, or *C* index. The medium room represents an *E* index, which similarly is a good average for the medium-utilization

classification of *D*, *E*, and *F* indexes. The small room has an index of *H* which is a fair average for the *G*, *H*, *I*, and *J* room proportions.

GUIDE FOR ESTIMATING NUMBER OF LAMPS REQUIRED FOR 50 FOOTCANDLE INSTALLATIONS*



FIXTURE	Light† Finish	Medium‡ Finish	Light Finish	Medium Finish	Light Finish	Medium Finish
	SQUARE FEET PER 40-WATT WHITE FLUORESCENT LAMP TO GIVE 50 FOOTCANDLES IN SERVICE					
0% Upward, 79% Down — Closed End Unit; 0% Upward, 80% Down — Open End Unit	23	22	20	18	16	15
17% Upward, 65% Down — Glass Louvers – White Reflectors; 33% Upward, 48% Down — Elliptical Specular Reflectors	19	17	16	14	13	12
23% Upward, 43% Down — Half Cylinder Plastic; 29% Upward, 43% Down — Wedge Unit Glass; 54% Upward, 27% Down — Open Top – Diffusing Bottom; 45% Upward, 25% Down — Open Top – Open Louvered Bottom	14	11	11	9	9	7

HOW TO USE THIS TABLE

Divide the total square feet to be lighted by the value from this table to determine the number of 40-watt white fluorescent lamps to be used. The number of fixtures required can thus be quickly calculated, depending on the number of lamps per fixture.

For example, if 6-lamp open-top, diffusing-bottom units are used to light a store 30 by 70 feet with a 13-foot ceiling and light walls and ceiling, the procedure is:

Number of lamps required for 50 footcandles $= \frac{30 \times 70}{11} = \frac{2100}{11} = 191$

Number of fixtures $= \frac{191}{6} = 32$

Thus 32 of these fixtures should be placed at existing outlets or located to give uniform lighting and a pleasing arrangement.

* Using 40-watt 48-inch white fluorescent lamps. If 40-watt daylight lamps are used, about 20% more lamps are needed. The average illumination in service will be around 50 footcandles. Due to depreciation of lamps and fixtures, the initial footcandle levels will be appreciably higher.
† Light ceiling (75 %) and wall (50 %) finish.
‡ Medium ceiling (50 %) and wall (30 %) finish.

FIG. 132.—A "pocket guide" for estimating the number of 40-watt fluorescent lamps required to produce 50 footcandles in service. Useful charts of this nature can be made up for specific fluorescent equipments.

To use such a tabulation, it is simply necessary to divide the total square feet to be lighted by the appropriate tabular value to get the number of 40-watt white fluorescent lamps needed. The number of fixtures desired can then be quickly calculated, depend-

ing on the number of lamps per fixture. Of course, the square feet per lamp given in such tables are calculated only for given types of candlepower distribution and for the specific output upward or downward as shown. However, once the lighting man thoroughly understands the influence of changes in outputs and differences in distribution characteristics, appropriate and accurate deviations can be quickly made from the table for the specific luminaire with which he is concerned.

Several manufacturers have shown in their fixture catalogues similar data in terms of "square feet per luminaire" for the specific luminaires they manufacture. Such data have been calculated for the distribution and output of those specific units and can, therefore, be used with considerable accuracy.

Although the data given in Fig. 132 are for 50 footcandles in service, it is extremely simple to calculate the square feet for lamp for any given footcandle level. For example, if 100 footcandles is desired, the tabular values should be divided by two. For 25 footcandles, they should be doubled. For any other illumination level, multiply the tabular values by the ratio 50 divided by the desired footcandle level.

Making Your Own Simplified Design Table.—To put design data in such a readily usable and easily remembered form for the specific fluorescent luminaires frequently encountered, simply use this formula

$$\text{Square feet per luminaire} = \frac{\text{(lumens per lamp)(number of lamps per luminaire)(coefficient of utilization)(maintenance factor)}}{\text{footcandles desired in service}}$$

Thus, handy tables can be made up for white or daylight lamps and for several footcandle levels. The lamp lumens can be obtained from Table 4 or from up-to-date published ratings of lamp manufacturers, Coefficients of Utilization can be obtained in many cases from the fixture manufacturer or can be calculated by the method briefly outlined in the Appendix, and the maintenance factor can be closely approximated by using the factor given in Table 29 for the general type of luminaire to which the specific fixture most closely approximates. Once these calculations are completed, they can be put in pocket notebooks

or made up on heavy paper as pocket-sized folders and conveniently "used on the job."

Supplementary Fluorescent Lighting.—The long, slender shape of fluorescent lamps makes them especially adaptable to use in continuous rows for many industrial and commercial services, such as the supplementary lighting of counter tops and work tables. The lamps have inherently a candlepower distribution that tends to build up the illumination along the axis of the row.

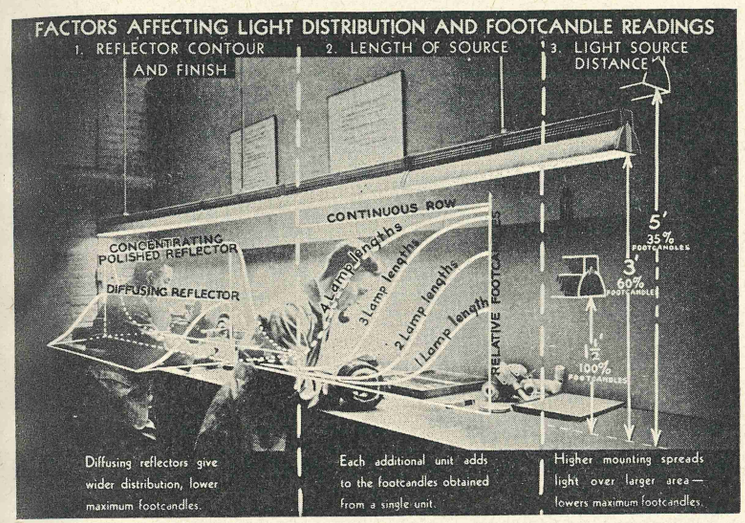


FIG. 133.—A composite representation of three factors affecting the distribution of light and the footcandles produced by trough types of supplementary lighting units.

The Coefficient of Utilization data contained earlier in this chapter apply only to general lighting and are, therefore, of little value in appraising the lighting results from supplementary systems. To facilitate such calculations, several charts are included here to indicate the footcandle levels that may be expected when using fluorescent lamps in various lengths of parabolic trough reflectors and mounted at several heights above the plane of measurement.

Although space does not permit the inclusion of footcandle curves of all the many supplementary lighting conditions, the results at other distances, for example, can be approximated by interpolation, and the illumination levels from multiple rows on known

spacings can also be estimated by addition. It will be also found necessary in practice to make certain adjustments for reflector size and shape and the number of louvers and their finish. Figure 133 shows the composite effect of the various factors that affect light distribution and footcandle readings from supplementary lighting troughs. Besides these three principal factors is a fourth which concerns the wattage size and color of the fluorescent lamps employed—the actual results will be proportional to the lumen output per foot of the lamp used.

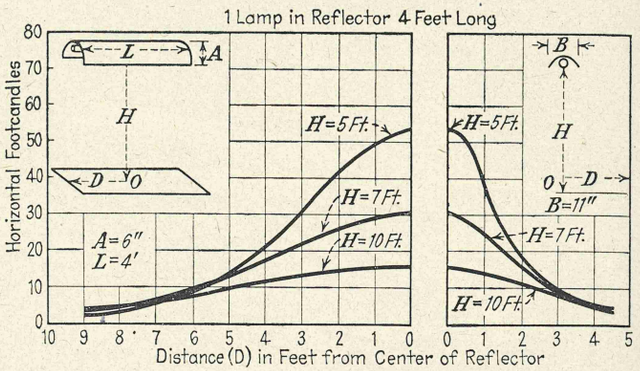


FIG. 134.—Distribution of horizontal footcandles on planes at various distances from a parabolic trough reflector of specular aluminum and with a 1⅛-in. focal length using 40-watt white fluorescent lamps. The curves are for one lamp in a reflector 4 ft. long.

Reflector Contour and Finish.—Obviously, reflectors that have diffusing surfaces give a wider distribution of the light and lower maximum footcandle levels than do polished-type reflectors (part 1 of Fig. 133). A more complete discussion of this subject was included in Chap. VI.

Porcelain enamel or white painted reflectors produce a widespread distribution. Specular metals such as polished aluminum (of proper contour and lamp position) will produce a more concentrated distribution, increasing the footcandles immediately below the reflector but fading off rapidly as the lateral distance from the axis of the lamp is increased. Although the total light output of both diffusing and concentrating types of reflector may be comparable, the latter types will produce perhaps double the footcandles directly below the unit as compared with the illumination under widespread or diffusing reflectors.

Trough Length.—As shown under part 2 of Fig. 133, each additional unit of length adds to the footcandle level obtained directly beneath the trough. This results because, as the light source becomes more extended, there will be an endwise overlapping and building up of the footcandles from adjacent reflectors. For example, the illumination level directly under the center portion of a 16-ft. continuous trough consisting of four 4-ft. sections will be approximately double that obtained under the center of a single 4-ft. section, other factors remaining constant. There is very little effect, however, when the section exceeds the former length.

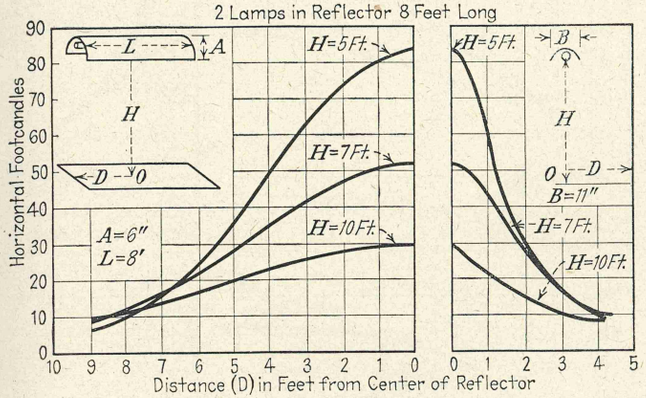


FIG. 135.—The same as Fig. 134—two lamps in a reflector 8 ft. long.

Figures 134, 135, 136, and 137 show the distribution of horizontal footcandles on planes at various distances from a parabolic trough reflector of specular aluminum having a 1⅛-in. focal length, when equipped with 40-watt white fluorescent lamps (present rated output—525 lumens per foot).[1] Figure 134 shows a single section 4 ft. long, illustrating both the lengthwise and the crosswise distribution of footcandles. The effect of two 4-foot sections in tandem (or a reflector 8 ft. long) is indicated in Fig. 135. Figure 136 is for three lamps in a reflector 12 ft. long and Fig. 137 is for five 40-watt lamps in a reflector 20 ft. long. A study of these curves will illustrate the effect of the trough length on the amount and distribution of footcandles produced.

[1] "Fluorescent Design Data," compiled by W. M. Potter and W. J. Eby of the Nela Park Engineering Department, General Electric Company.

These curves are also useful in planning fluorescent trough lighting for supplementary illumination.

Height above Work Surface.—Notice in Fig. 137 that the footcandle level directly beneath the center of the trough is about

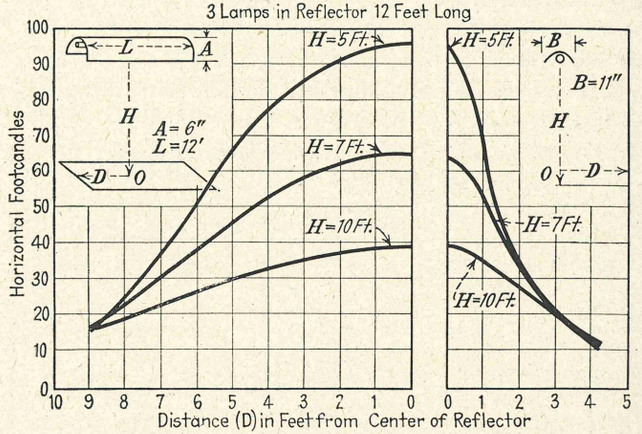


FIG. 136.—The same as Fig. 134—three lamps in a reflector 12 ft. long.

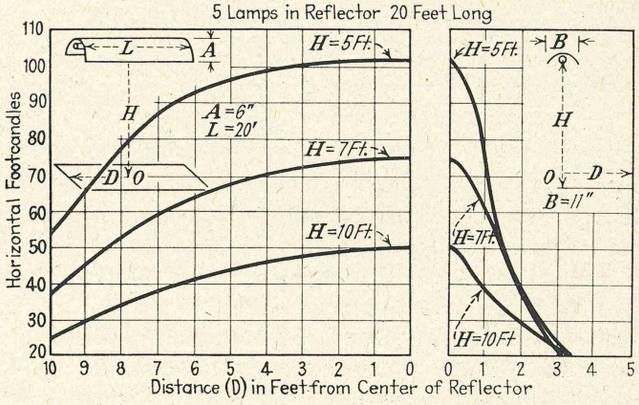


FIG. 137.—The same as Fig. 134—five lamps in a reflector 20 ft. long.

half as much at a mounting height of 10 ft. as compared with a mounting height of 5 ft. This again illustrates the fact that the inverse square law does not apply when measuring illumination levels at such relatively small distances from large area or extended sources. If the inverse square law did apply, the

footcandle level at 10 ft. would be about one-fourth that of the illumination level at 5 ft.

Of course, these figures vary with individual reflectors and mounting heights. It is important to emphasize that, although higher mounting heights spread the light out over larger areas and lower the maximum footcandles, the distances involved in the usual supplementary-lighting installation are often insufficient for the inverse square low to become operative. Doubling the mounting height will usually result in lowering the footcandles

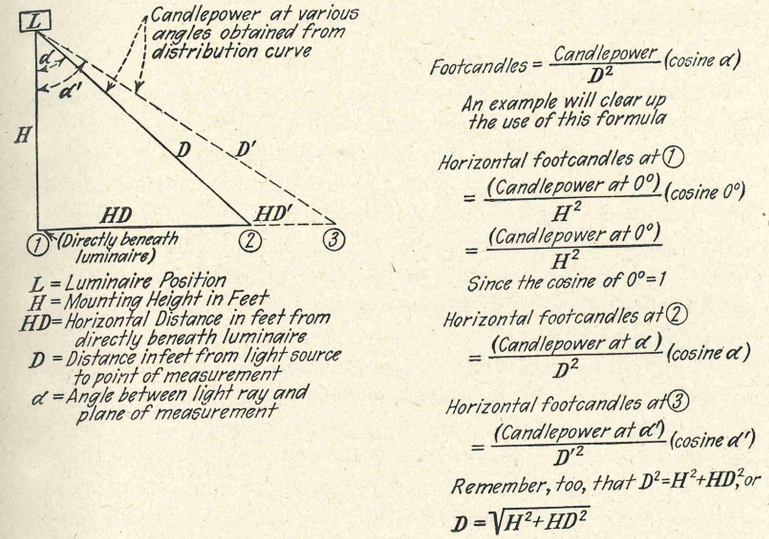


FIG. 138.—The fundamental approach to point-by-point calculations.

to one half or one third, instead of to one quarter which might be expected.

However, the inverse square law can be used with accurate results in illumination calculations involving fluorescent lamps provided the distances are at least five times the maximum dimensions of the source. As earlier mentioned, in the case of a 4-ft. fixture this means a distance of at least 20 ft. Fluorescent luminaires are rarely mounted at that distance from the work plane except in high-bay factory areas, in which case the illumination calculations can be made with the point-by-point method. This method is useful for determining the direct illumination at

definite points in the work plane where (1) there is little reflection of light from the surroundings and (2) the distance from the source is large compared with the size of the source. The point-by-point method has been used for many years with filament-lamp luminaires employed in downlighting and other types of lighting systems and consists simply of determining how much light is contributed to the illumination at any definite point by all the luminaires around it. The basic formula is

$$\text{Horizontal footcandles} = \frac{\text{candlepower}}{(\text{distance in feet})^2}\left(\begin{matrix}\text{cosine of angle between light}\\ \text{ray and plane of measurement}\end{matrix}\right)$$

This nomenclature is explained in Fig. 138.

Luminous Element.—Fluorescent lamps are especially useful light sources for luminous architectural elements (employed either for illumination or decoration) because they are extended sources of high efficiency and are available in several colors. The brightnesses of fluorescent lamps are sufficiently low to permit a relative freedom in the selection of materials from a diffusion standpoint. Even such low diffusion materials as unfinished and depolished clear glasses and plastics may frequently be employed without fear of excessive maximum brightnesses and undesirable contrasts. However, in elements carrying advertising messages or silhouette decoration (transom areas in store fronts, for example), requirements for clarity of pattern on distant view will suggest the use of highly diffusing materials when they are lighted by the lamps directly. Fluorescent lamps are also well adapted to many other types of luminous elements.

The actual positioning of fluorescent lamps in the luminous element depends on the average brightness desired,[1] the distribution of brightness considered acceptable, and the available space. The element efficiency will be higher but the brightness less uniform if lamps are placed close to a translucent panel, for example, within a very shallow white cavity. Generally

[1] The basic formula for the brightness of a luminous element is

$$\text{Footlamberts} = \frac{(\text{lamp lumens})(\text{element efficiency})(\text{maintenance factor})}{\text{square feet of luminous area}}$$

Element efficiencies are available in several illumination-design handbooks, including "Illumination Design Data," *Bulletin* LD-6A, Nela Park Engineering Department, General Electric Company.

speaking, rows of fluorescent lamps should be positioned with respect to the glass in the same manner as are rows of filament lamps. A uniform brightness of highly diffusing materials can be obtained when the crosswise spacing between rows of lamps is at least one and a half times the distance from the glass or diffusing material to the lamp axis. Figure 139 indicates the permissible limit in end-to-end spacing to secure uniform brightness with highly diffusing glass. These data are based on observations made on flashed-opal glass panel 9 in. wide and lighted by one row of fluorescent lamps centered behind it in a cavity of 75 per cent reflection factor. It should be remembered

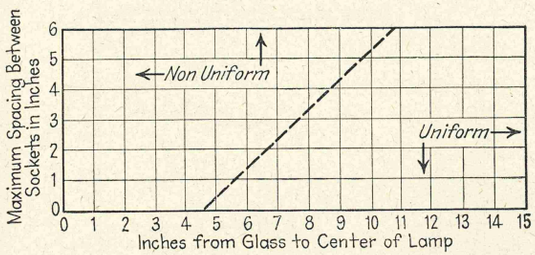


FIG. 139.—The approximate permissible limit of end-to-end spacing of new fluorescent lamps for a luminous panel of highly diffusing glass. The data are based on observations of a panel of flashed-opal glass 9 in. wide and lighted by one row of fluorescent lamps centered behind it in a cavity of 0.75 reflection factor. Spacing should be reduced somewhat in anticipation of fluorescent-lamp end blackening.

that even when the sockets are in end-to-end contact with each other, a space of about 1⅜ in. still exists between the ends of adjacent luminous areas of the lamps. Greater spacings are permissible with increases in (1) the sizes of the panel, (2) the distance from glass to the lamp, (3) the reflectivity of the cavity, and (4) the average brightness.

Show-window Lighting Design.[1]—A new method for designing show-window illumination has been developed, making possible for the first time considerable accuracy in predicting levels of illumination on show-window lines of trim from both filament and fluorescent lamps. These representative planes of trim are shown in cross section in Fig. 140. They are those commonly used in trimming windows and provide a reference location for measurement of show-window illumination.

[1] W. J. EBY, "Design Data for Show Window Lighting," *Folder* F, Nela Park Engineering Department, General Electric Company.

The basic formula used in this method is

$$\text{Average footcandles in service} = \frac{\text{illumination factor}}{\text{window depth (in feet)}} \text{ (length factor) (shielding factor)}$$

The illumination factors are found in Table 31 for fluorescent reflectors having three types of distribution: widespread, semi-concentrating, and concentrating. Data are given in Table 31 for each zone in the show window and for the entire window, all

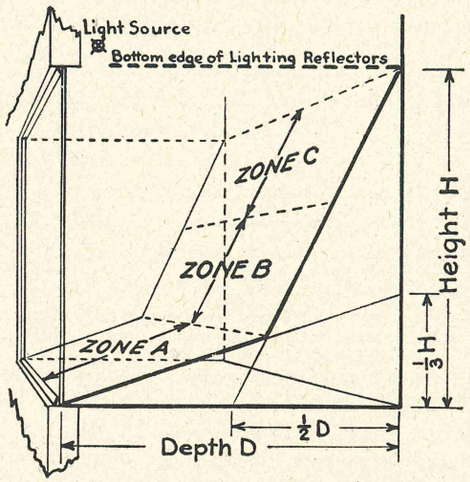


FIG. 140.—The show-window lines of trim.

illumination factors representing an "in-service" condition, because a maintenance factor of 75 per cent has already been applied. The data in this table also indicate the relative illumination to be expected from reflectors of these three different types and with different numbers of rows. In planning the show-window lighting system, it is, of course, best to select the combination of reflector and lamp that will provide the most favorable distribution of the illumination for a given zone.

The length factors are given in Table 32 for white fluorescent lamps. If daylight fluorescent lamps are employed, these length factors should be changed in proportion to light output. The length factor involves a consideration both of the light output per foot of windows and the fact that light is utilized more

TABLE 31.—ILLUMINATION FACTORS FOR SHOW-WINDOW LIGHTING DESIGN
(Depreciated to average service value; maintenance factor of 0.75 used)

H/D ratio	Type of equipment*	Illumination factors															
		2 rows of lamps			4 rows of lamps			6 rows of lamps			Over-all		
		Zone A	Zone B	Zone C	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C	2 rows of lamps	4 rows of lamps	6 rows of lamps
4.0	Widespread	50	25	80	85	40	160	Not usually possible to install 6 rows of lamps in windows with these H/D ratios			55	110	
	Semi-concentrating	50	30	125	75	40	290				75	140	
	Concentrating	70	45	115	100	55	250				80	160	
3.5	Widespread	60	30	80	105	55	210				60	130	
	Semi-concentrating	60	45	125	95	55	300				80	160	
	Concentrating	90	55	120	125	70	255				85	170	
3.0	Widespread	75	45	85	135	70	225				70	140	
	Semi-concentrating	80	55	125	135	80	310				90	180	
	Concentrating	120	70	110	165	100	260				100	200	
2.5	Widespread	90	60	90	165	110	240	195	130	450	80	170	260
	Semi-concentrating	100	75	125	175	135	310	220	200	480	100	205	305
	Concentrating	160	80	100	225	145	250	250	240	480	110	220	325
2.0	Widespread	110	80	100	210	150	255	260	200	470	100	205	315
	Semi-concentrating	130	100	125	225	200	310	310	320	460	115	245	365
	Concentrating	210	105	80	310	230	230	365	365	460	130	260	395
1.5	Widespread	150	120	90	285	220	260	395	330	480	120	250	400
	Semi-concentrating	175	130	120	320	255	280	470	415	445	140	285	445
	Concentrating	280	120	70	470	285	200	590	440	415	155	315	485
1.0	Widespread	210	155	55	400	340	225	570	500	465	150	320	495
	Semi-concentrating	250	155	110	470	340	225	780	500	420	180	360	555
	Concentrating	375	110	40	730	250	110	1070	420	210	200	415	625

* Widespread—diffuse aluminum reflector, output 65 per cent.
Semi-concentrating—specular aluminum reflector, output 85 per cent.
Concentrating—asymmetric specular aluminum reflector, output 80 per cent.

TABLE 32.—LENGTH FACTORS FOR SHOW-WINDOW LIGHTING DESIGN
(White fluorescent lamps)

Length available per row, feet	Lamp combinations possible in each row	Window length, feet																					
		3		4		5		5½		6		7		8		10		12		15	
		Glass at one end	Walls at both ends	Glass at one end	Walls at both ends	Glass at one end	Walls at both ends	Glass at one end	Walls at both ends	Glass at one end	Walls at both ends	Glass at one end	Walls at both ends	Glass at one end	Walls at both ends	Glass at one end	Walls at both ends	Glass at one end	Walls at both ends	Glass at one end	Walls at both ends
2	1—24 in.	0.45	0.50	0.60	0.65	0.75	0.80	0.70	0.75												
3	1—36 in.	0.70	0.75	0.90	0.95																
4	1—48 in.	....	....	....	....	0.75	0.80	0.70	0.75												
5	1—36 in. and 1—24 in.	....	....	....	....	0.85	0.90	0.80	0.85	1.30	1.40	1.20	1.25	1.10	1.15						
	1—60 in.	....	....	....	....	1.50	1.60	1.40	1.50												
5½	1—48 in. and 1—18 in.	....	....	....	....	....	....	0.90	0.95	0.85	0.90										
6	2—36 in.	....	....	....	....	....	....	....	....	0.90	1.00	0.85	0.90	0.75	0.80						
7	1—48 in. and 1—36 in.	....	....	....	....	....	....	....	....	....	....	1.00	1.05	0.90	1.00	0.80	0.85				
8	2—48 in.	....	....	....	....	....	....	....	....	....	....	....	....	1.10	1.15	0.95	1.00				
9	3—36 in.	....	....	....	....	....	....	....	....	....	....	....	....	....	....	0.95	1.00				
10	2—48 in. and 1—24 in.	....	....	....	....	....	....	....	....	....	....	....	....	....	....	1.15	1.20	1.00	1.05	1.40	1.45
11	2—60 in.	....	....	....	....	....	....	....	....	....	....	....	....	....	....	1.90	2.00	1.65	1.75		
	3—36 in. and 1—24 in.	....	....	....	....	....	....	....	....	....	....	1.00	1.05	0.90	1.00	....	....	1.05	1.10	0.90	0.95
12	3—48 in.	....	....	....	....	....	....	....	....	....	....	....	....	1.10	1.15	....	....	1.25	1.30	1.05	1.10
13	1—48 in. and 3—36 in.	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	1.10	1.15
14	3—48 in. and 1—24 in.	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	1.20	1.25
15	5—36 in.	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	1.20	1.30
15	3—60 in.	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	2.10	2.20

These factors have been calculated on the basis of the following light output values:

Lamp	Lumens
15 watts; 18 in.	615
20 watts; 24 in.	900
30 watts; 36 in.	1450
40 watts; 48 in.	2100
100 watts; 60 in.	4200

If a lamp with a different output is used, these factors should be changed in proportion to light output.

efficiently in the longer windows. Appropriate lamp combinations per row are also indicated for the various window lengths.

The shielding factors are shown in Table 33 for various H/D ratios (the ratio of height to depth, obtained by dividing the window height by the depth) and for matte white louvers of the common egg-crate variety having a crosswise shielding angle of 45 deg. and a lengthwise shielding angle of 25 deg. Of course, if louvers are not used, the shielding factor will be unity.

TABLE 33.—SHIELDING FACTORS FOR SHOW-WINDOW LIGHTING DESIGN

H/D ratio	Shielding factors Egg-crate louvers* shielding lamps to 45 deg. crosswise and 25 deg. lengthwise		
	Zone A	Zone B	Zone C
4.0	0.90	0.83	0.88
3.5	0.90	0.83	0.88
3.0	0.90	0.85	0.88
2.5	0.90	0.85	0.88
2.0	0.90	0.85	0.86
1.5	0.92	0.87	0.84
1.0	0.92	0.91	0.79

* Matte white.

For example, suppose it were desired to provide about 100 footcandles in zone A of a show window 10 ft. long, 3 ft. deep, and 6 ft. high with two wall ends. White 40-watt fluorescent lamps are to be used in louvered reflectors. Assume that because of the ceiling construction it is possible to use only two lamps end-to-end in each row.

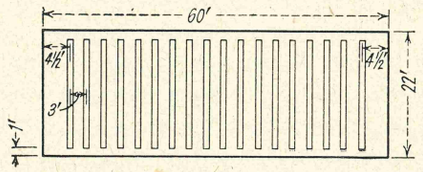
The H/D ratio is $\frac{6}{3}$, or 2, and from Table 32 it will be seen that the length factor is 1.0 and from Table 33 that the shielding factor is 0.90. By working backward from the formula previously given,

$$\text{Illumination factor} = \frac{(\text{average footcandles in service})(\text{depth in feet})}{(\text{length factor})(\text{shielding factor})}$$

which, in this particular case, is

$$\text{Illumination factor} = \frac{(100)(3)}{(1.0)(0.90)} = 333$$

From Table 31, it will be seen that this illumination factor in zone *A* can almost be secured by using four rows of concen-



Ceiling height, 13 ft. 0 in.
Ceiling finish: Very light, reflectance, 75 per cent
Wall finish: Fairly light, reflectance, 50 per cent

1	Recommended footcandles	50
2	Lighting system and type of equipment	40-watt fluorescent troffers
3	Room index	F
	Coefficient of utilization	0.48
	Maintenance factor (M.F.)	0.75
	Area of room	1320 sq. ft.
4	Lamp lumens required for 50 footcandles	183,333
	Lamp lumens per luminaire (40 watt white fluorescent lamps)	2,100
5	Approximate number of luminaires	88
	Luminaires per continuous row (crosswise of room) 22 ÷ 4	5
	Number of rows (lengthwise of room)	18
	Spacing between rows (rows on centers)	3 ft. (see sketch)
	Spacing between outer rows and walls	4½ (see sketch)
6	Maximum permissible spacing between rows	13
	Maximum permissible spacing between outer rows and walls	4*
	Actual number of luminaires	90 4-ft. sections
7	Footcandles in service $= \frac{\text{number luminaries} \times \text{luminaire lumens} \times \text{C. of U.} \times \text{M.F.}}{\text{room length} \times \text{width}}$	$\frac{(90)(2100)(0.48)(0.75)}{1320}$ = 51.5 footcandles
8	Watts per square foot (include auxiliaries) $\frac{\left[\frac{(2)(40) + 17.5}{2}\right]90}{1320} = 3.3$	3.3

* The 4½-foot spacing between outer rows and walls actually used does not seriously exceed the maximum of 4 ft.

FIG. 141.—A typical illumination problem, lighting a business office to 50 footcandles with 40-watt troffers.

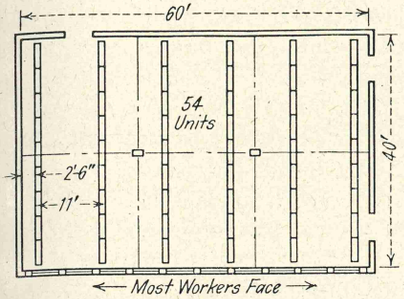
trating reflectors. The actual foot-candles in service in zone *A* will equal

$$\text{Actual footcandles secured} = \frac{310}{3}(1.0)(0.90) = 93$$

These tables on show-window design are based on the following angles of reflector tilt:

Equipment	Rows	Angle of Tilt, Degrees
Widespread	1–3	14
	4–6	22
Semi-concentrating	1–6	14
Concentrating	1–6	22

Of course, the illumination will vary from that calculated if an angle of tilt other than the above is used. In some cases, it may be desirable to use an adjustable mounting in order to obtain the most favorable distribution of illumination.



Ceiling height, 12 ft.
Ceiling reflection, 50 per cent
Wall reflection, 50 per cent
Machines or benches may be placed along all walls
The work includes die and tool making and a high quality, high-level general lighting installation is wanted.

1. Recommended footcandles	50
2. Lighting system and lighting equipment	RLM fluorescent
3. Selection of number of units	
a. Room index (based on 10 ft. 6 in. mounting)	C
b. Coefficient of utilization (C.U.)*	0.66
c. Maintenance factor (M.F.)	0.75
d. Computations:	
(1) Lumens per sq. ft. (recommended footcandles) delivered in service	50
(2) Lumens per sq. ft. delivered initially (#1 ÷ M.F.)	66.7
(3) Lumens per sq. ft. generated (#2 ÷ C.U.)	101
(4) Lumens per unit†	4200
(5) Square feet per unit (#4 ÷ #3)	41.5
(6) Area of room in sq. ft.	2400
(7) Number of units required (#6 ÷ #5)	58
(*a*) Actual number of units installed	54
(*b*) Average footcandles in service $= \frac{\text{number of units} \times \text{lumens per unit} \times \text{M.F.} \times \text{C.U}}{\text{sq. ft. area}}$	$\frac{(54)(4200)(0.75)(0.66)}{2400} = 47$
4. Location of units	
a. Maximum allowable spacing between units (or rows)	10–12 ft.
b. Maximum distance from walls	3½–4 ft.
c. Actual layout‡	Shown on sketch

* From Table 29.
† For white lamps at present rating. The lumens per unit would be 3600 for 40-watt daylight lamps.
‡ 40-watt RLM units are 52½ in. long so units in a continuous row would be on 52½-in. centers.

FIG. 142.—An industrial lighting problem of the type commonly encountered.

A Practical Fluorescent Lighting Problem.—Figure 141 illustrates the procedure and calculations required to plan a fluorescent-troffer lighting system of 50 footcandles in service for a typical office area. Perhaps the simplest part of such a design problem is following the procedure outlined earlier in this chapter—often the seemingly most difficult points are determined by "horse sense" alone.

For example, if the workers in this particular office face the long way of the room (as they very likely would), it would be logical to run the troffers crosswise of the room. Each troffer section is 4 ft. long, so only five sections could be put in a continuous row across the 22-ft. width. This would leave a space of 1 ft. between the end of each row and the side wall. A spacing of 3 ft. on centers was selected because most fluorescent troffers have an opening 1 ft. wide, being designed to replace one row of acoustical ceiling material. If the section of acoustical ceiling material and the fluorescent troffer are each 1 ft. wide, then the troffers must be located on even multiples of 1-ft. spacing. A troffer spacing on centers of 3 ft. (2 ft. of acoustical material between troffers) gives slightly over 50 footcandles in service in this particular case.

Figure 142 illustrates a similar procedure and calculations for an industrial fluorescent lighting problem using continuous rows of two-lamp RLM fluorescent reflectors. Of course, once the procedure and the general principles of fluorescent illumination design have been mastered, the calculations can be made without resort to such a "form."

Planning for Tomorrow's Footcandle Levels.—Since fluorescent lamps lack any interchangeability of wattage sizes, provision for future increases in footcandle levels must be provided for by

1. Making the initial layout flexible enough to accommodate additional luminaires or rows of units which can be installed later but which will be coordinated with the original layout.
2. Using luminaires in which provision has been made for adding an additional lamp or lamps in the future.

The first requirement can be accomplished by spacing the luminaires in a straight line in such a manner that the spaces between luminaires are equal to the length of one unit. Then the space could be exactly filled in a continuous-row form by adding a luminaire at some future date.

Regarding the second, some industrial-type reflectors for two lamps are punched for a third lamp which when added later will inexpensively enable a 50 per cent footcandle boost.

CHAPTER VIII

COLOR QUALITY

Exploring the Spectrum.—Fluorescent lamps, like other light sources, are simply generators of radiant energy. They produce and emit energy over a certain range of wavelength or frequency, just as radio transmitters send out energy but of one given wavelength tremendously longer than visible radiation or light. There are many other radiant-energy sources, such as *X*-ray tubes, heat lamps, and radium—even the radiators by which rooms are heated. All these sources produce exactly the same nature of radiation but of different wavelengths and frequencies.

Figure 143 pictures the complete electromagnetic spectrum, showing the location of the radiant energy that the eyes receive as light. Figure 143 has not been drawn to scale; if it had been, the visible spectrum of light would be but a minute portion. All electromagnetic radiations have a common characteristic, that of being propagated through space at the same rate. This velocity is 299,860,000 m. per sec., or about 186,000 miles per sec. The product of the wavelength and the frequency is equal to this constant velocity. Thus the greater the wavelength, the less will be the frequency.

The common unit for wavelength measurement around the visible portion of the electromagnetic spectrum is the angstrom, equal to about four billionths of an inch. Other wavelength units are given in Table 34. The eye acts much the same way as a receiver in that it is tuned to wavelengths ranging from approximately 3800 to 7200 Å. The color sensation that energy within that region (or light) produces depends on how that energy is distributed among the various color regions of the visible spectrum. Figure 144 shows an expanded view of the visible spectrum and indicates the approximate color divisions. Of course, there is no sharp demarcation between the blue and green, for example. In fact, scientists say that there are all of 128 "just perceptible color differences" within the visible spectrum.

TABLE 34.—UNITS OF WAVELENGTH AND EQUIVALENTS

Unit and symbol	Meter	Centimeter	Millimeter	Micron	Millimicron	Angstrom unit	Inch
Meter (m.).....	1	100 10^2	1000 10^3	1,000,000 10^6	1,000,000,000 10^9	10,000,000,000 10^{10}	39.37
Centimeter (cm.).	0.01	1	10	10,000 10^4	10,000,000 10^7	100,000,000 10^8	0.3937
Millimeter (mm.)	0.001 10^{-3}	0.1 10^{-1}	1	1000 10^3	1,000,000 10^6	10,000,000 10^7	0.03937
Micron (μ).....	0.000001 10^{-6}	0.0001 10^{-4}	0.001 10^{-3}	1	1000 10^3	10,000 10^4	0.00003937
Millimicron (mμ)	0.000000001 10^{-9}	0.0000001 10^{-7}	0.000001 10^{-6}	0.001 10^{-3}	1	10	0.00000003937
Angstrom unit (Å.).	0.0000000001 10^{-10}	0.00000001 10^{-8}	0.0000001 10^{-7}	0.0001 10^{-4}	0.1 10^{-1}	1	0.000000003937
Inch (in.).....	0.0254	2.54	25.4	25,400	25,400,000	254,000,000	1

1 Å. = approximately 4 billionths of an inch.
Velocity of light = 2.9986×10^{10} cm. per sec., or 186,000 miles per sec.
Wavelength (cm.) × frequency = 30,000,000,000 (approximate speed of light in centimeters per second).
One light year = 5.9×10^{12} miles.

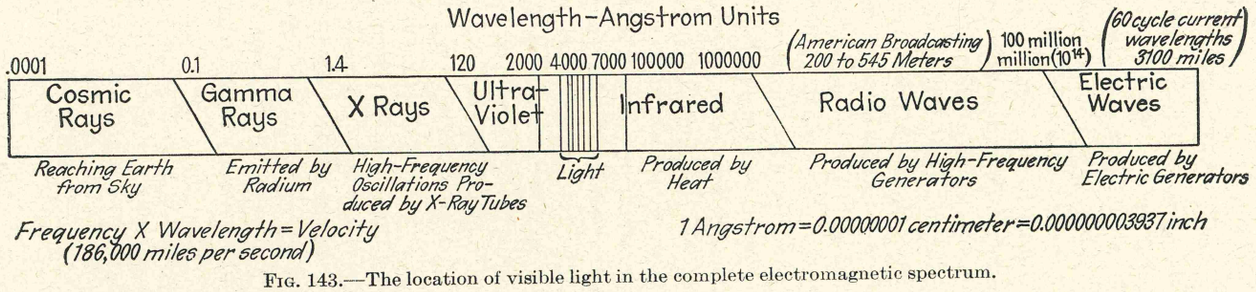


FIG. 143.—The location of visible light in the complete electromagnetic spectrum.

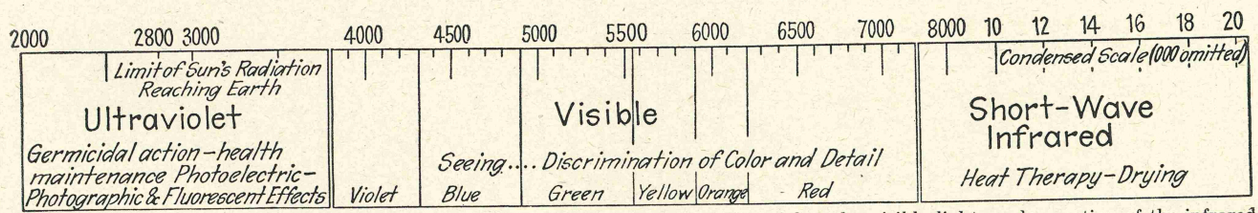


FIG. 144.—An expanded view of the electromagnetic spectrum showing the ultraviolet, the visible light, and a portion of the infrared region.

Equal energies of the various wavelengths in the visible spectrum do not all produce the same sensation of brightness in the eye. This effect is shown in Fig. 145, called the "eye-sensitivity" or "luminosity" curve, and is representative of the average human eye. It will be seen that the maximum eye sensitivity is in the yellow-green region. If it were possible to produce a lamp in which all the energy were concentrated at the single wavelength at which the eyes are most sensitive, that lamp could have an efficiency of around 620 lumens per watt. To date, the maximum efficiency obtained even with laboratory lamps is around 100 lumens per watt.

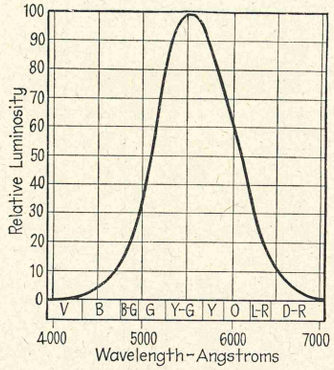


FIG. 145.—The sensitivity or luminosity curve of the average eye.

How Spectral Distribution Curves Are Obtained.[1]—A spectral-distribution curve simply indicates how much energy is radiated by a particular lamp at the various wavelengths. These spectral-energy measurements are made with the spectrophotometer. The heart of such instruments is a diffracting or refracting device which spreads the incident beam of light into a spectrum of the colors of which that incident light is made up. Every high-school physics student learns that a prism, for example, bends the light rays, the shorter wavelengths being bent more than the longer ones. White light is known to be a mixture of all colors, for when white light is passed through a prism, a spectrum of all the colors of the rainbow results. Figure 146 shows this effect.

Most spectrometric instruments have a movable slit by which the component colors spread out by a refracting or diffracting device can be scanned a small band at a time. The energy that comes through the slit can then be measured either by comparison with a laboratory standard of known intensity or by a radiant-energy meter of some type (Fig. 147). This energy can be measured in watts or microwatts (a millionth of a watt). The slit is constructed to have a width of so many angstroms, 100 or 200 Å. widths are common in spectrophotometer slits, and its position in the visible spectrum can be calibrated. Thus it is possible to measure the energy in these relatively small bands adjacent to each other throughout the visible spectrum. Figure 148 shows these bands for the continuous spectrum of an incandescent-filament lamp.

[1] "Interpretation of Spectral Distribution Data in Practical Color Applications" by R. L. Oetting and C. L. Amick, presented at the 1941 Annual Convention of the Illuminating Engineering Society and published in the December, 1941, issue of *Illuminating Engineering*. Several of the illustrations contained in this chapter were developed by Mr. Oetting and the writer for presentation to that society.

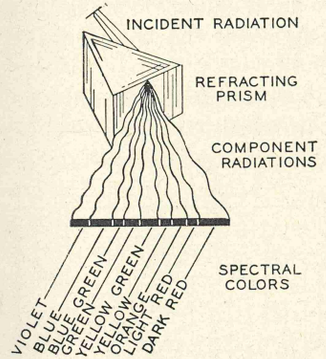


FIG. 146.—A refracting prism breaks up the incident light into its component spectral colors.

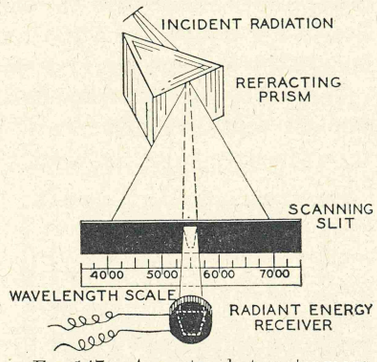


FIG. 147.—A spectrophotometer measures the energy within a certain wavelength band determined by the width of the scanning slit.

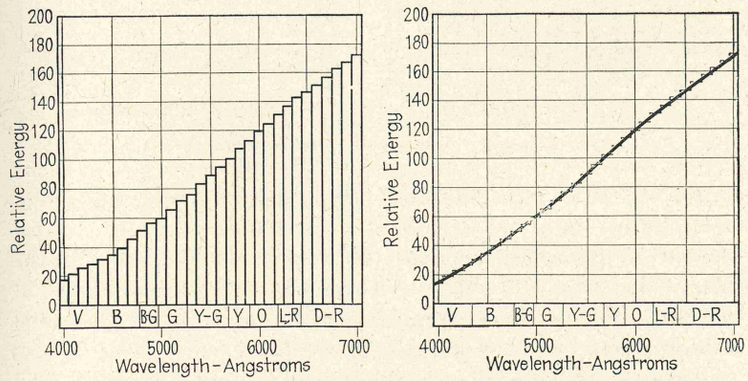


FIG. 148.—Blocks of energy representing spectrophotometer measurements every 100 Å. throughout the visible spectrum emitted by an incandescent filament lamp.

Since the slits of spectrophotometers have an appreciable width, the energy measured by the receiving instrument represents the total energy within a "band" at that particular position in the visible spectrum. Therefore, it is the area within the plotted bars which denotes the spectral energy and not the height of the bars. However, if the bars are all of equal width (as they always are in any given test), the heights of the bars indicate the relative average energy in each band.

Figure 148 was for a filament lamp in which the spectrophotometer slit width was 100 Å. If the slit width had been 200 Å., approximately twice the energy would have passed through the

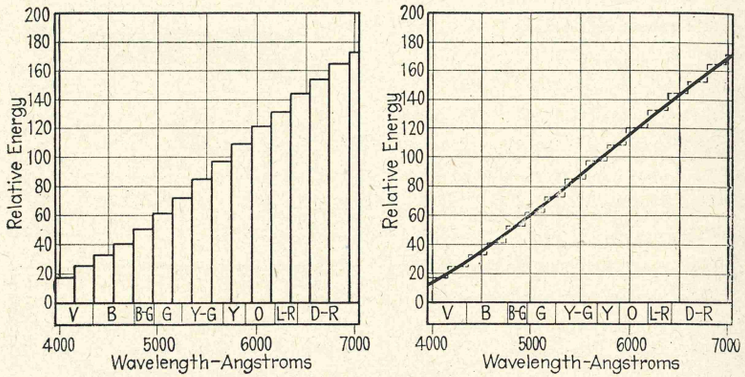


FIG. 149.—The same for 200 Å. widths.

slit for any given position in the visible spectrum and so the area plotted would be about twice that of the 100 Å. slit width. With the bar width being doubled, the height will remain approximately the same and still give twice the area contained within the bar. This is shown graphically in Fig. 149 for the same filament lamp but with 200 Å. slit widths.

Of course, if extremely small slit widths were physically possible, the bars could be made very narrow and would approach a smooth curve. But it is not usually practical to measure bands much less than 100 Å. wide, and sometimes they are as wide as 400 Å. A smooth curve can be produced by connecting the center point of the tops of the bars, the assumption being that the energy at the mid-point of the band is representative of the average energy throughout that band.

Light sources, such as incandescent-filament lamps, which have no gaps or sudden changes in their distribution of energy in the visible spectrum are spoken of as "continuous-spectrum" sources. However, when spectral-energy measurements are made of a fluorescent lamp, it will be seen that occasional bands are considerably brighter than those adjacent. This is illustrated in Fig. 150 for a white fluorescent lamp and a 200 Å. slit width. The difference in brightness of those occasional bars is even greater when 100 Å. widths are employed. These higher energy bands are caused by the "line radiation" of the low-

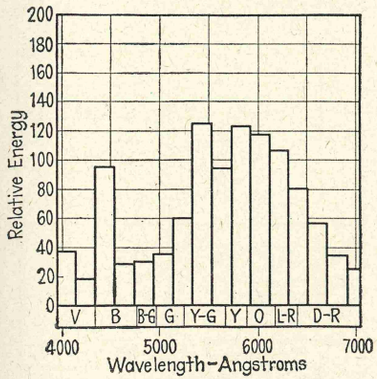


FIG. 150.

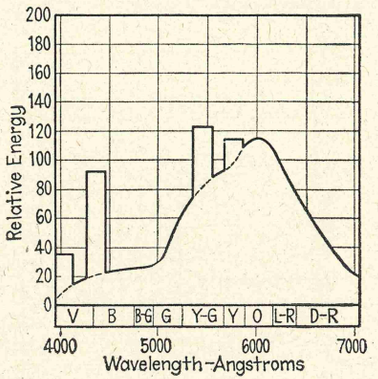


FIG. 151.

FIGS. 150 and 151.—(Left) Comparable 200-Å. bars representing the measurements on a white fluorescent lamp. Note that occasional bands are brighter than those adjacent. (Right) The conventional spectral distribution curve of a discontinuous source is made up of a continuous and a projected bar portion such as this for a white fluorescent lamp.

pressure mercury arc within the tube. This simply means that energy is concentrated at a single wavelength, and these lines pass through phosphor and glass and appear in the resultant spectral distribution. Such lamps are called "discontinuous-spectrum" sources, and their spectral-distribution curves are plotted as shown in Fig. 151 and consist of (1) a continuous and (2) a line spectrum portion, the latter being shown as bars of area above the continuous portion. These projected bars are centered on the position of the mercury line whose energy they represent (the visible lines for the low-pressure mercury arc within the fluorescent lamp have wavelengths of 4047, 4358, 5461, and 5780 Å.). The height of the bars is determined by the

bar width, the area above the continuous portion of the spectral-distribution curve indicating the magnitude of the energy in that particular line.

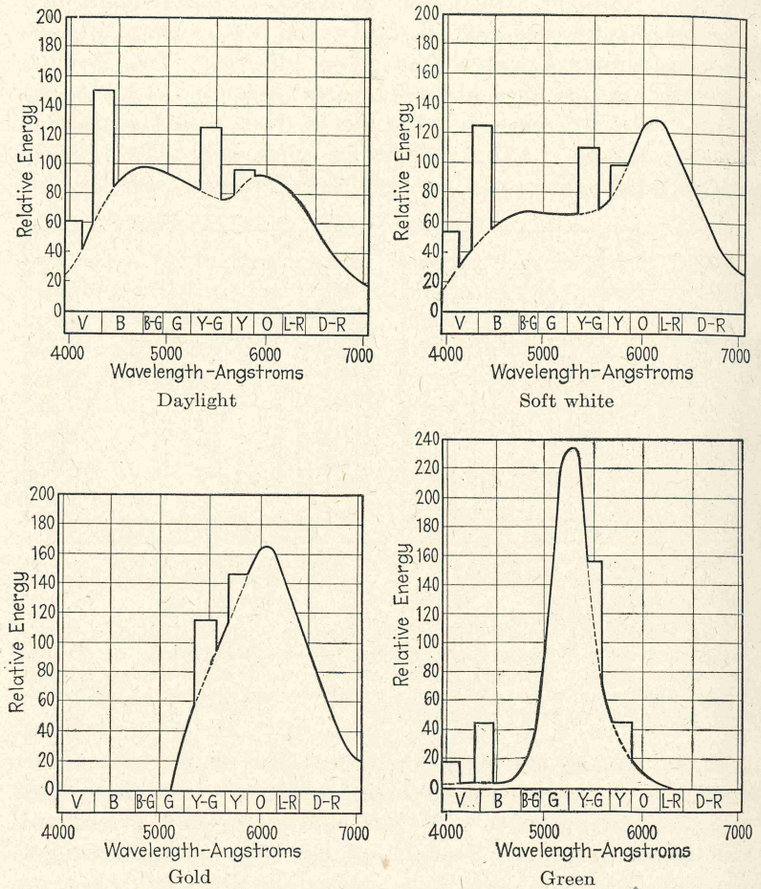


FIG. 152.—For descriptive legend see opposite page.

How Spectral Curves Indicate the Fundamentals of Color.—Figure 152 shows the spectral-distribution curves of seven of the standard fluorescent lamp colors, all drawn on the basis of equal lumen outputs.[1] Table 4 indicates that various colored lamps have quite different lumen outputs. These illustrations simply

[1] Figure 151 is for the white lamp.

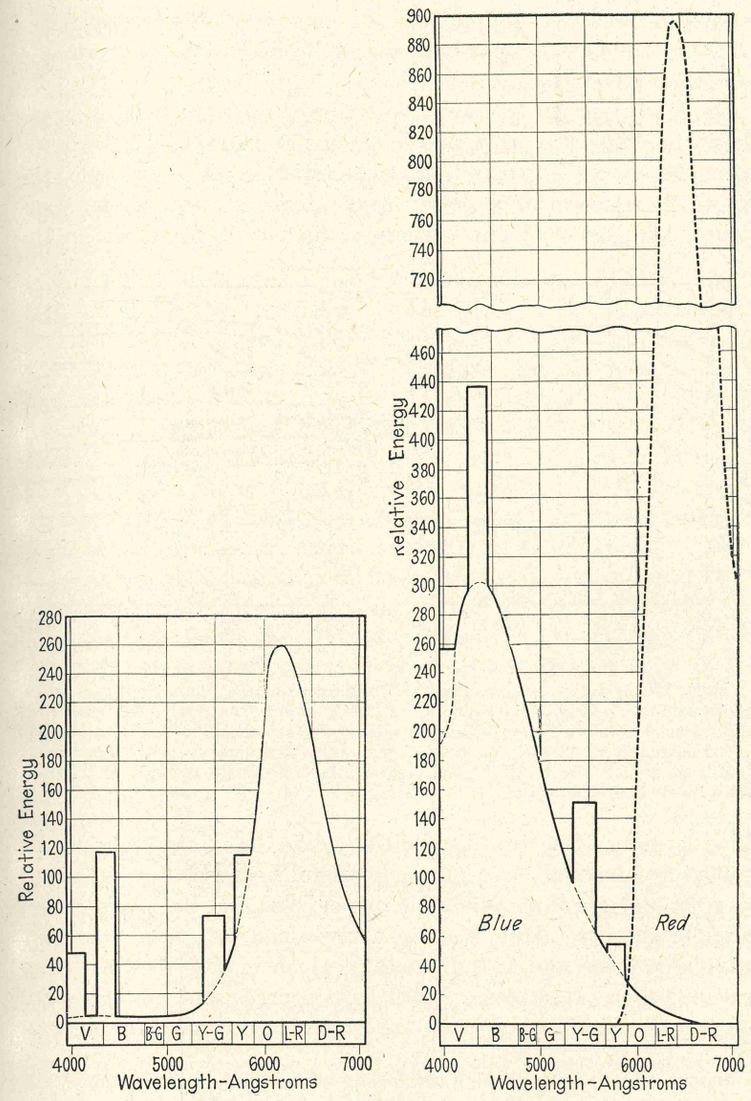


FIG. 152.—Conventional spectral distribution curves for the daylight, soft white, gold, green, pink, blue, and red fluorescent lamps. Distribution of the white lamp is shown in Fig. 151.

show the relative proportions of energy in the wavelengths emitted by each lamp which would be necessary to produce a given number of lumens.[1]

A study of these spectral-distribution curves will indicate how the color of a light source can be approximately predicted from its spectral distribution characteristics. For example, the green fluorescent lamp peaks in the green portion of the spectrum, and, as would be expected, the blue lamp peaks in the

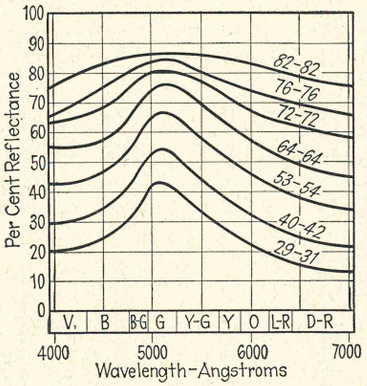


FIG. 153.

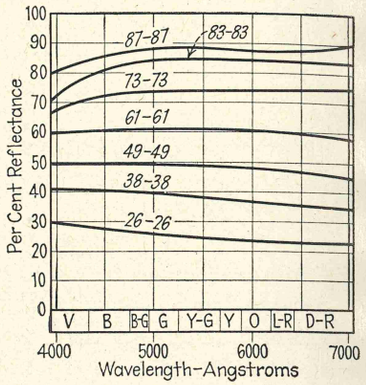


FIG. 154.

FIGS. 153 and 154.—(Left) Spectral reflectance curves for a family of green paint samples. (Right) The same for a family of gray samples. The numerical figures shown above these curves are reflectance factors. The figure at the left is for incandescent filament lamps and will apply in general for white fluorescent lamps as well. The figure at the right is the reflectance to light of daylight fluorescent lamps.

blue region. Spectral-distribution data of light sources or reflecting materials are extremely useful because they illustrate or represent the three fundamentals of color, *i.e.*, hue, saturation, and brightness. Hue has been described as "the colorful" part of a color and is that quality which is described as being green, yellow, blue, etc. Most light sources and materials are composed of many hues that are synthesized by the eye into an

[1] Obviously, there is nothing mysterious about the light from fluorescent lamps. The glass used in fluorescent bulbs is almost completely opaque to the short-wave ultraviolet, and normal human eyes should not be harmed by the light from these lamps. The subject is further discussed by Dr. Matthew Luckiesh, director of the Lighting Research Laboratory, General Electric Company, in *Magazine of Light*, No. 4, 1941.

apparent single color value which is designated by the spectral region or hue that it most closely matches.

Saturation is illustrated by Fig. 153 which shows spectral-reflectance curves for a series of green paint samples. The different paint samples were obtained by adding increasingly larger amounts of green color pigment to white paint. The top curve representing the nearly white color (it has a slight greenish tint) has no dominant peak or trough and is, therefore, considered as relatively unsaturated or neutral. As more green pigment is added, the peak in the green spectral region becomes more dominant and the color is more saturated. As might be expected, the grays (Fig. 154) are practically unsaturated, so the samples obtained by successively adding an increasing amount of black paint to white remain neutral but simply of lower reflectance values.

Reflectance Factors.—The brightness of a color is defined as the ratio of the light which that given color reflects as compared with that reflected by a theoretically perfect 100 per cent white color. In more common parlance, this ratio is considered the reflectance factor of that color. However, even though the average height of a spectral-reflectance curve is an indication of the brightness of a sample, it cannot be used directly as the reflectance factor for the latter is a luminosity and not an energy function. Therefore, the eye-sensitivity curve must be applied to both the energy falling on the sample and the energy reflected by the sample. Table 35 shows how reflectance factors are obtained mathematically.

How the Spectral Quality of a Lamp Influences Reflectance Factors.—The gray samples shown in Fig. 154 have practically no saturation but do have different brightnesses as indicated by the curve heights. Having no color of their own, they take on the hue of the source by which they are lighted, and such neutral or unsaturated colors will have virtually the same reflection factor for light of almost any spectral quality. Table 35 showed that this was not true for the highly saturated sienna sample on which those calculations are based.

This difference in reflection factor of the same sample under two different illuminants is due to the fact that the sample does not reflect certain wavelengths in the visible spectrum so efficiently as it does certain others. The energy available for that

TABLE 35.—REFLECTION-FACTOR CALCULATIONS*

Wave length	Spectral energy		Eye sensitivity	Spectral reflectance	Luminosity			
					Incandescent		Daylight fluorescent	
	Incandescent	Fluorescent			Source	Sample	Source	Sample
(1)	(2)	(3)	(4)	(5)	(6) = (2) × (4)	(7) = (5) × (6)	(8) = (3) × (4)	(9) = (5) × (8)
4000	16.0	26.1	0.0004	0.08	0.01	.....	0.01	
4100	19.0	38.4	0.0012	0.08	0.02	.....	0.05	
4200	22.3	52.2	0.0040	0.08	0.08	0.01	0.21	0.02
4300	26.0	64.5	0.0116	0.08	0.30	0.02	0.75	0.06
4400	30.0	75.8	0.023	0.08	0.68	0.05	1.74	0.14
4500	34.0	86.2	0.038	0.08	1.30	0.10	3.27	0.26
4600	38.5	94.5	0.060	0.08	2.32	0.19	5.67	0.45
4700	43.0	98.5	0.091	0.08	3.91	0.31	8.96	0.72
4800	48.0	97.5	0.139	0.08	6.66	0.53	13.55	1.08
4900	53.0	95.5	0.208	0.09	11.03	0.99	19.87	1.79
5000	58.1	92.6	0.323	0.09	18.77	1.69	29.89	2.69
5100	63.6	90.1	0.503	0.10	32.00	3.20	45.31	4.53
5200	69.1	87.1	0.710	0.11	49.09	5.40	61.87	6.81
5300	75.0	83.7	0.862	0.12	64.63	7.76	72.14	8.66
5400	81.1	80.7	0.954	0.13	77.46	10.07	77.02	10.01
5500	87.3	77.7	0.995	0.15	86.85	13.03	77.39	11.61
5600	93.6	75.8	0.995	0.17	93.15	15.84	75.44	12.82
5700	99.6	78.8	0.952	0.20	94.84	18.97	74.98	15.00
5800	105.6	86.6	0.870	0.23	91.88	21.13	75.39	17.34
5900	111.6	90.6	0.757	0.26	84.49	21.97	68.57	17.83
6000	117.6	91.6	0.631	0.29	74.21	21.52	57.78	16.76
6100	123.4	90.1	0.503	0.31	62.08	19.24	45.31	14.05
6200	129.1	86.6	0.381	0.32	49.17	15.73	33.02	10.57
6300	134.9	79.8	0.265	0.34	35.76	12.16	21.14	7.19
6400	140.6	68.9	0.175	0.35	24.60	8.61	12.06	4.22
6500	146.3	58.1	0.107	0.35	15.64	5.47	6.21	2.17
6600	151.6	48.2	0.061	0.36	9.24	3.33	2.94	1.06
6700	156.7	39.6	0.032	0.37	5.01	1.85	1.27	0.47
6800	161.9	32.5	0.017	0.38	2.75	1.05	0.55	0.21
6900	166.9	25.6	0.0082	0.38	1.37	0.52	0.21	0.08
7000	171.7	19.7	0.0041	0.39	0.70	0.27	0.08	0.03
4047	.....	63.8	0.0006	0.08	.....	.....	0.04	
4358	.....	148.9	0.0177	0.08	.....	.....	2.64	.21
5461	.....	88.2	0.9843	0.14	.....	.....	86.85	12.16
5780	.....	20.1	0.889	0.22	.....	.....	17.82	3.92
					1000.00	211.01	1000.00	184.92
				Reflection factor	$\frac{211}{1000} = 21\%$		$\frac{184.9}{1000} = 18\%$	

[1] From "Interpretation of Spectral Distribution Data in Practical Color Applications," by R. L. Oetting and C. L. Amick, *Illuminating Engineering*, December, 1941.

particular sample to reflect is determined by the spectral-distribution curve of the light source by which that sample is illuminated. Thus, a particular material can have a different reflection factor to illuminants of widely different spectral characteristics, as was shown by Table 35 for the filament and daylight fluorescent lamps.

Appearance of Colored Materials.—Although colored materials will not have the same reflection factors for light sources of different spectral quality, even greater may be the differences in the appearance of a color sample under two sources. For example, complexions and clothing look differently under sodium-vapor lighting than under incandescent lighting, appearances are still different under the blue-green light or mercury-vapor lamps seen in printing plants, mortuaries, etc. Although the spectral characteristics of fluorescent lamps are not so different from those of filament lamps as in the cases just cited, there were some misunderstandings about color appearance when fluorescent lamps were first introduced. This was natural because of the public's long familiarity with the appearance of various materials under filament lighting.

The principal reasons for a difference in the appearance of colored materials under fluorescent as compared with incandescent-filament lighting are

1. The relatively lower proportion of energy in the red end of the fluorescent-lamp spectrum.
2. The presence of the mercury-line radiations.

This difference in appearance can be easily explained by considering the spectral characteristics both of colored objects and the light source.

Since a certain amount of experience is necessary before accurate predictions of color appearances can be made from spectral data, Table 36 is included to show how various common colors appear under daylight fluorescent, white fluorescent, soft-white fluorescent, and incandescent-filament lighting. Also, it is unlikely that spectral-distribution data will be available for many of the colored surfaces that enter the everyday lighting problem.

In specifying fluorescent lighting wherever color discrimination or color quality is an important factor, it should be remembered that

TABLE 36.—APPEARANCE OF SOME PAINTED COLOR SURFACES UNDER FLUORESCENT AND INCANDESCENT-FILAMENT LAMPS

Color names were first assigned to the samples as they appeared under the fluorescent daylight lamp since this light most closely simulates natural daylight. The other color names, reading from left to right, for each color and tint are related as much as possible to those in the first left-hand column. The fact that color changes take place with tungsten-filament lamps as well as with the white and soft-white fluorescent lamps is illustrated.

Fluorescent daylight	Incandescent (60-watt filament)	Fluorescent white	Fluorescent soft white
(C) Grayed greenish yellow	Golden yellow (free from greenishness)	Grayed yellow (slight green)	Yellowish buff
(T) Ivory (bluish)	Deep ivory	Ivory (yellowish)	Ivory (pinkish)
(C) Medium blue	Very grayed purplish blue	Slightly purplish blue	Light purplish blue
(T) Pale blue	White*	Pale bluish gray	Pale bluish purple
(C) Medium brown (coolest)	Medium brown (slightly orange)	Medium brown (slightly warmer)	Medium brown (slightly pink)
(T) Very pale pink	Pale reddish buff	Pale pinkish buff	Grayed purplish pink
(C) Deep purple (bluish)	Deep purple (reddish brown)	Deep purple (less bluish)	Deep purple (reddish)
(T) Pale bluish purple	Pale yellowish red	Grayed reddish purple	Medium reddish purple
(C) Medium green-blue	Medium blue-green	Grayed medium blue	Grayed medium blue (slightly purplish)
(T) Very pale blue	White*	Pale bluish gray	Very pale purplish white
(C) Very grayed dark green	Grayed yellow-green	Grayed green (slightly yellowish)	Grayed green (slightly brownish)
(T) Very pale green-blue	Medium ivory	Pale buff	Very pale purplish gray
(C) Deep rose	Medium red	Grayed medium red	Medium rose
(T) Light pink (slightly purplish)	Yellow-red (very pale)	Light pink (warmer)	Light pink (redder)

(C) Full color.
(T) Tint of color.
* In each case, four samples of the same color were viewed under the four light sources at the same time. The starred colors marked white only appeared so by comparison with the other three samples. By turning off the other three lamps and viewing these samples alone, the bluish quality of both returns. Surrounding these samples with a white surface will also cause the bluish appearance to return.

1. The daylight lamp is a very close approach to natural daylight—its deficiency in the red end of the visible spectrum emphasizes the blues and purples but so does natural daylight. By all scientific criteria, the daylight fluorescent lamp is a much more natural color for an illuminant than the light from incandescent-filament lamps.

2. The white fluorescent lamp (3500°K.) radiates more energy of yellow-green, yellow, and orange colors and will emphasize those hues.

3. The radiations from the soft-white fluorescent lamp peak in the orange and light-red portion of the spectrum but do not emphasize the yellow-green colors. Its color is more flattering to complexions and make-up than either daylight or white fluorescent lamps. Also, the soft-white lamp gives meats and other foodstuffs a natural appearance.

4. The incandescent-filament lamp, because it is so rich in the red portion of the spectrum, emphasizes the warm colors.

Of course, some customers may prefer a combination of white and daylight fluorescent lamps rather than the exclusive use of either color. Combinations of these lamps in luminaires or in luminous elements provide a color temperature between 3500 and 6500°K. (depending on the proportion of each color used), resulting in greater flexibility and often increasing the attractiveness of the luminaire. Also, the purple cast apparent on some blue colors (certain clothing, hats, etc.) when viewed under the 3500° white fluorescent lamp can be overcome by adding daylight lamps or changing one or more lamps in a luminaire to daylight. Mirrors of standard greenish plate glass may be responsible for complaints on color in clothing stores and other locations where mirrors are involved in careful color appraisals. Such mirrors absorb more of the deep red light than of other colors, and where fluorescent lamps are used, the lower proportion of red energy is aggravated. The problem can be solved by substituting a colorless glass mirror or by using partial red filters for the fluorescent lamps in the mirror-lighting units.

The fading of merchandise is discussed in Chap. IX.

Matching Daylight.—Figure 155 shows a spectral-distribution curve of completely overcast skylight having a color temperature of 6500°K. The light is a mixture of (1) sunlight and (2) skylight filtered through the clouds. An artificial-light source would have to duplicate the relative energy-distribution curve of some such daylight standard if materials of *any color* were to appear the same under both the natural daylight and the artificial lighting.

A light source having the spectral qualities of natural daylight has always been desired, and blue-bulb so-called daylight fila-

ment lamps have long been available and used for widely different applications. However, this "subtractive" method is a costly one from the standpoint of lamp efficiency, since the blue-bulb tungsten-filament daylight lamp has an output of only about 50 to 60 per cent of the ordinary inside frosted lamp. Filament daylight lamps have a color temperature of 3500 to 4000°K. Other daylight filters have been available, but great sacrifices must be made in over-all efficiency if the spectral quality of natural daylight is to be closely matched. For example, one type of glass when used with a 500-watt incandescent-filament lamp will produce a good match for daylight at 6500°K. but

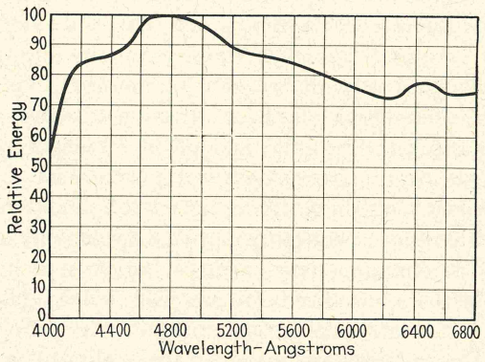


FIG. 155.—The spectral distribution curve of completely overcast skylight having a color temperature of 6500°K.

transmits only about 17 per cent of the light from the lamp. Daylight would thus be produced at an efficiency of only about 3½ lumens per watt. It is not surprising that a daylight fluorescent lamp producing light of this quality at an over-all efficiency of some 35 lumens per watt was welcomed by the public and the lighting industry.

Tests show that the appearance of many color samples is practically the same under natural-daylight and fluorescent daylight lamps. However, certain color-matching problems are very critical and should be referred to the color expert. Too, remember that for certain inspection tasks involving the detection of small color differences, the illuminant should be rich in the spectral region at which the samples have maximum absorption. Thus, in detecting small color differences in blue materials,

it is better to use a tungsten-filament lamp (which is rich in red) than the daylight fluorescent lamp rich in blue. On the other hand, small differences in yellows, pinks, and reds are more clearly revealed by the daylight fluorescent lamp.

The daylight lamp is actually a more reliable color-matching illuminant than is natural daylight because the latter varies so with seasons, during the day, etc. The spectral distribution and thus the color temperature of fluorescent lamps are not affected to any practical degree by variations in line voltage, and the color temperature is also practically constant throughout the life of the lamp.[1] For these reasons, the daylight fluorescent lamp is being used for many applications today where color matching or color discrimination are important. Figures 178 and 179 illustrate one application of fluorescent lamps for color matching.

Color Temperature.—Color temperature, in a popular sense, refers to the degree of whiteness of a light source. Color-temperature measurements are obtained by comparing the color of the light source under consideration with that of a standard laboratory radiator (called a "black-body" radiator) heated to the proper temperature to give the same color of light.

Strictly speaking, color-temperature values cannot be assigned to light sources whose color differs widely from that of the laboratory standard or black-body radiator. However, in the case of a lamp that will not exactly match in color the radiation from a black body at any temperature, but will *approximately* match it at some definite temperature, it may be assigned an approximate color temperature representing the nearest color match. Both the daylight and the white fluorescent lamps can be assigned a definite color temperature—6500°K. for the daylight and 3500°K. for the white lamps[2]—but none of the remaining fluorescent colors can be accurately given a color-temperature rating because their radiations differ so in hue with the black-body radiator.

Figure 156 indicates the color temperatures of natural daylight and various artificial-light sources. The chart illustrates how the "variable" natural daylight can be matched by both

[1] Any "apparent" change is probably due to brightness depreciation.

[2] The "degree Kelvin" is an absolute scale equivalent to degrees centigrade + 273. The color of a white fluorescent lamp, for example, would be similar to that of an incandescent black body (say, of carbon) at a temperature of 3227°C., or 3500°K.

filament and fluorescent lamps. The color temperatures of fluorescent lamps and combinations contained in Fig. 156 are based on the color response of the eye which may differ from the response of photographic emulsions.

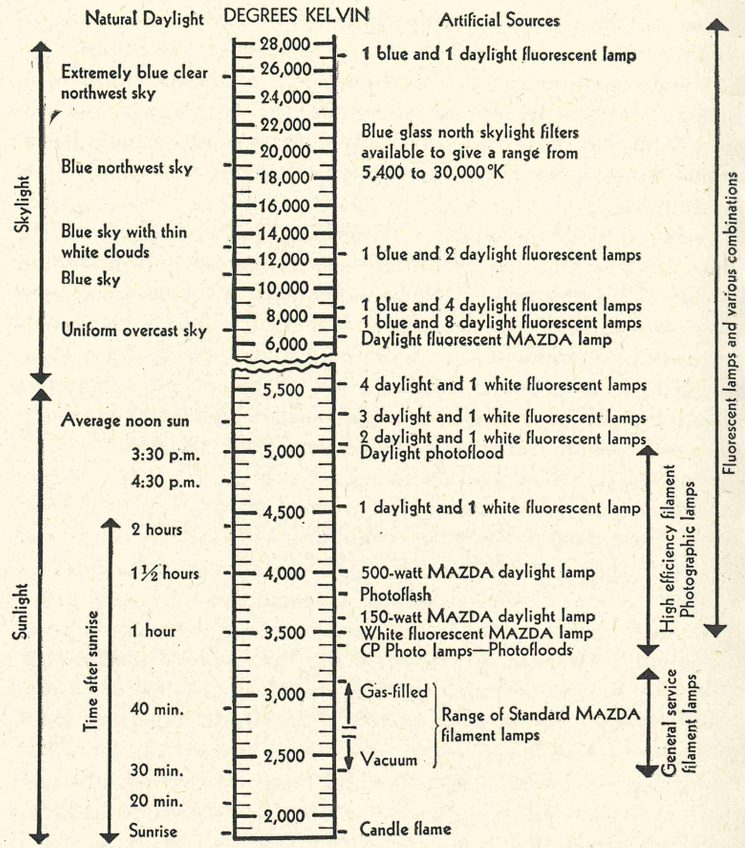


FIG. 156.—The color temperature of various phases of natural daylight and of several artificial-light sources and combinations.

Actually, by proper combination of the various colored fluorescent lamps, the color quality of the light can be blended to obtain any color temperature. In this manner, colored or tinted illumination in the room can be regulated at will by proper combinations of lamps of various colors. Where several lamps are

used to form a geometric design or in multilamp luminaires, lamps may be chosen to form lighted color patterns at the ceiling, yet produce a blended illumination of any whiteness or tint desired at the working plane. Figure 207 illustrates this scheme of producing white light at the floor of a large auditorium by combining light from coffers employing colored fluorescent lamps.

Although combinations of colored lamps have several special uses in illumination work, their proper mixture is frequently a delicate proposition.

1. If the resultant mixture of light is to have a suitable spectral character, each color should contribute its proper portion of the total light.

2. Space the lamps in such a way that the colored light will be well mixed by the time it approaches the floor plane where complexions, food, clothing, etc., must appear reasonably natural.

3. Give careful attention to the aesthetic and psychological possibilities of color.[1]

The light from colored fluorescent lamps can be adequately mixed by properly alternating the lamps. The proportion of the various colors to use in securing a pleasing result is, however, more complicated.

TABLE 37.—COMBINATION OF COLORED FLUORESCENT LAMPS TO SECURE VARIOUS COLOR TEMPERATURES*

Colors in combination	Per cent of total light to get					
	3000°K.	3500°K.	5000°K.	6000°K.	6500°K.	10,000°K.
Blue	17	22	36	40	42	51
Gold	83	78	64	60	58	49
Blue	2	7	18	25	28	40
Green	39	39	39	37	36	29
Pink	59	54	43	38	36	31
Blue	6	11	22	27	30	43
Green	61	59	54	51	49	40
Red	33	30	24	22	21	17

* See text for explanation of method.

[1] This latter point has been thoroughly discussed in several books on the application of color to interior decorations.

Some two- and three-color combinations which have found practical use are given in Table 37 with tabular values indicating the percentage of total light required to produce various approximate color temperatures. The relative numbers of the various colored lamps can be determined from Table 37, for the number of each color needed is directly proportional to the percentage of total light it contributes and inversely proportional to its lumen output. For example, to determine the relative numbers of blue, green, and pink 30-watt fluorescent lamps to produce light

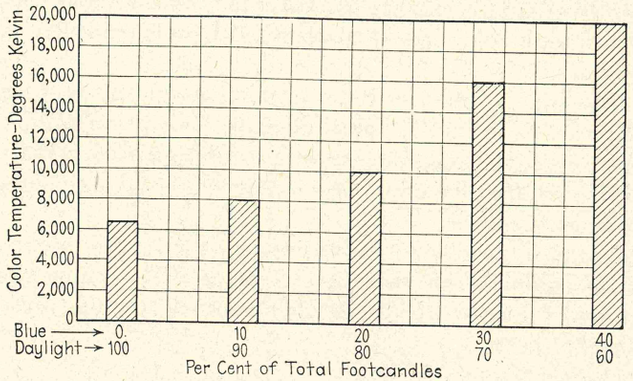


FIG. 157.—The color temperatures which result when the light of blue fluorescent lamps is mixed with that from daylight fluorescent lamps.

at 6500°K., simply divide the tabular values by the lumen outputs as follows:

$$N_b:N_g:N_p = {}^{28}\!/_{780}:\ {}^{36}\!/_{2250}:\ {}^{36}\!/_{750} = 9:4:12 \text{ approximately}$$

Thus, out of twenty-five 30-watt lamps, nine should be blue, four green, and twelve pink if the combination is to have an approximate color temperature of 6500°K.

By simply mixing daylight and blue fluorescent lamps, extremely high color temperatures can be obtained as shown in Fig. 157.

Color Flicker.—Table 13 gives the stroboscopic effect, or cyclic flicker, of various colored fluorescent lamps. In addition to this variation in light output, there is also a color flicker which results because about 10 per cent of the light of daylight, white, and soft-white lamps comes directly from the mercury arc. This light has a blue-green color, and it drops to zero 120 times per

second just as the lamp current does. Therefore, fluorescent lamps usually produce a slight color flicker in addition to the stroboscopic effect.

Of course, the means described to reduce stroboscopic effect also are effective in minimizing this color flicker.

Fluorescent Haze.—Some people have insisted that they can notice a "haze" under fluorescent lighting supposedly due to fluorescence of the eye. But tests prove that there is considerably less near ultraviolet energy per footcandle from fluorescent lamps than from natural skylight. The near ultraviolet, or haze, is simply "drowned out" by the visible light.

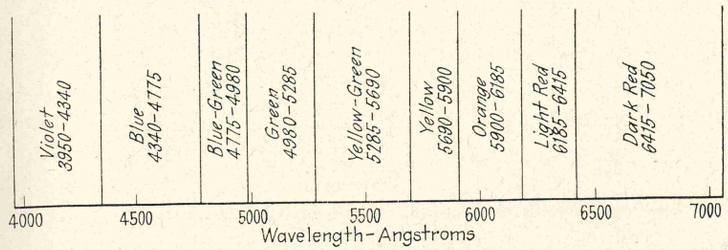


FIG. 158.—The division of the spectrum into nine color blocks used in the simplified step diagrams mentioned.

The so-called haze noticed is likely due to the usual irradiation surrounding a bare lamp rather than to the presence of any appreciable ultraviolet energy.

Simplified Step Diagrams.—As might be expected, several systems have been devised for indicating spectral-distribution data on a more simplified form than the conventional continuous-curve–projected-block method. One plan consists of breaking down the visible spectrum into steps having an equal number of "just perceptible color differences." It was learned many years ago that there are 128 just perceptible color differences in the pure spectral colors, and Fig. 158 shows the spectrum divided into 9 bands, of which 7 contain 16 just perceptible color differences and the other two (in the red region) contain 8 each. The single color name by which these spectral bands can be described are also shown in Fig. 158. Figure 159 shows the use of such block diagrams in comparing the daylight fluorescent lamp with natural daylight. It will be seen that in most bands the differences are small and the green and yellow mercury lines from the lamp do

not unbalance the color. Although the fluorescent lamp has a red deficiency in the long wavelength portion of the visible spectrum, it is in the region where the luminosity of the energy is low.

It is suggested that those sufficiently interested in the subject of color and color quality consult some of the references on this subject.[1] Many of the seeming complexities with which this subject has been surrounded are cleared up after a little study, and experience leads to considerable accuracy in predicting the

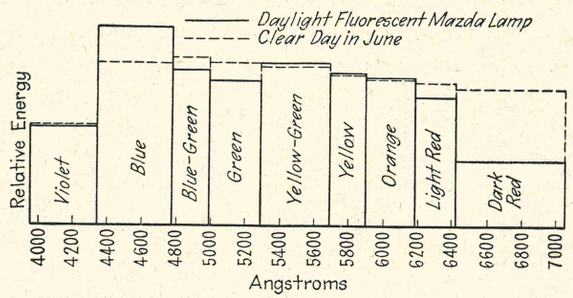


FIG. 159.—Simplified step diagrams for the daylight fluorescent lamp and for a clear day in June.

appearance of colored materials from their spectral-distribution data.

TABLE 38.—LIGHT-METER CORRECTION FACTORS

Light Source	Multiply Reading by
Filament lamps	1.00
White fluorescent lamps	1.00
Daylight fluorescent lamps	0.90
Soft-white fluorescent lamps	1.00
Blue fluorescent lamps	0.53
Green fluorescent lamps	1.20
Pink fluorescent lamps	0.93
Gold fluorescent lamps	1.20
Red fluorescent lamps	0.66
Blue-white type RF lamps	0.75
Industrial white type RF lamps	0.82

Light Meter Correction Factors.—Because the spectral response of the photoelectric cell used in the light meter and

[1] Block diagrams for all fluorescent-lamp colors will be found in the paper "Interpretation of Spectral Distribution Data in Practical Color Application" referred to earlier in this chapter.

similar portable footcandle meters does not coincide with the eye-sensitivity curve of the eye, correction factors must be applied when measuring illumination under light sources whose spectral distributions are considerably different from that to which the cell was calibrated. Table 38 gives these correction factors for the standard light meter.

Accurate footcandle measurements are frequently made by using a brightness meter and a diffusely reflecting surface of known reflectivity. However, careful calibration of the light meter and the application of the proper correction factors to compensate for spectral quality result in light-meter measurements sufficiently true for most commercial lighting work.

It will be noticed in Table 33 that of the sources commonly used for general lighting the light meter reads higher than the actual illumination for the daylight fluorescent and the type RF lamps. Therefore, the meter reading must be reduced by applying the factors designated.

CHAPTER IX

FLUORESCENT APPLICATIONS

A single chapter devoted to fluorescent-lamp applications can hardly do the subject justice. In the 4 years since its introduction, this revolutionary new light source has found a place in so many lighting fields (with more types of applications becoming apparent daily) that a whole volume would be required to describe completely and illustrate the evolution of fluorescent lighting and show some of the modern installations.

Yet despite its rapid acceptance, the fluorescent lamp is considered by most lighting people as but a partner to the simple, reliable incandescent-filament lamp. There are still many illumination jobs that can best be performed by the latter; for example, few can envision the use of anything but filament lamps in projection or spotlighting equipment, where optical control and precision are of the greatest importance. On the other hand, fluorescent lamps have enabled real advances toward well-known goals of comfortable-level general illumination—have, in short, lifted all lighting from the doldrums even to the extent of enticing many newcomers into the illuminating field.

In the preceding chapters, many of the fundamentals of fluorescent lamps have been discussed—auxiliary equipments, servicing, luminaire selection, and illumination design. Most of the principles have been rather simple, requiring little or no mathematics or engineering. Yet illuminating engineering is far from being a haphazard profession where general "rules of thumb" are used as substitutes for more exact engineering methods. To secure effective, comfortable lighting is an art, even though psychological considerations and personal preference often influence the final decision on which type of lighting system will be chosen.

One important dividend of careful planning and engineering design is the greater assurance of customer satisfaction. Fluorescent-lighting equipment is, generally speaking, more expensive

than comparable filament-lamp equipment. Thus, if an installation does not come up to expectations, the customer can easily be disappointed and therefore more dissatisfied because of the relatively large cash outlay. The public is remarkably light conscious and realizes the value of more and better light for seeing, selling, and production. But the customer who is misled into converting an old installation to a more up-to-date one without *significant improvement in the illumination level* may soon discover that he has paid a high price for what may in certain respects be branded as still obsolete because the "new" system was sold as a novelty rather than as a means of improving existing seeing or display conditions.

Well-established illuminating engineers take pride in their work because of its humanitarian aspects—eyesight, health, and energy conservation. This pride is evidence of their desire to serve the customer's illumination needs by (1) pointing out the need for (and the advantages of) increased footcandle levels and (2) making installations in which lighting quality is not compromised to the extent that quick and easy seeing is impaired. The final objective of fluorescent lighting (and all illuminating engineering for that matter) is to better the conditions under which people work and live, to make lighting yield its full contribution to human welfare, and to evoke emotions that are pleasant and satisfying. But regardless of these other factors, unless seeing requirements are fully met, the major purpose of a lighting system is defeated and no amount of decorative art can make up for this deficiency.

The Seeing Task.—Much has been written in the past few years about the science of seeing. This science is just what the name implies—the coordination and alignment of facts about the various aspects of light and vision as determined by many years of laboratory research into the realm of seeing. These researches have provided a reservoir of scientific data, forming standards on which to appraise present and future lighting in the goal toward better, cheaper, and more abundant light for civilization's needs.

There are three elements that make up the seeing process. They are (1) the eye, (2) the seeing task, and (3) the light which makes it possible for the eye to see. Light is the only controllable factor in the seeing process—there is little that can be done for the eyes themselves (except to provide glasses if such aid is

needed), and the seeing task is rarely controllable. However, every lighting man should appreciate the factors that influence the visibility of the seeing task.

There are four such factors: (1) the size of the object, (2) the extent to which it contrasts with its background, (3) the time available for seeing, and (4) the brightness of the object. The first factor is an obvious one, for everyone knows that the larger an object, the easier it can be seen. The amount of light available also influences the ability to see small objects. Light is, in fact, a magnifier of small detail. In this way, light functions in much the same manner as do eyeglasses for those who need them.

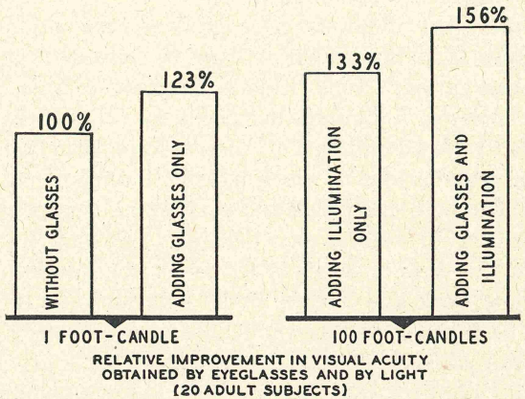


FIG. 160.—The relative improvement in visual acuity obtained by the use of eye glasses and by light as revealed by a test on twenty adult subjects.

Figure 160 shows the relative improvement in visual acuity (which simply means the ability to see small detail) obtained by (1) providing the proper eyeglasses and (2) by raising the illumination level. It will be seen that a greater improvement in visual acuity was obtained in this test by adding the illumination alone than by adding glasses without changing the footcandle level.

Contrast, the second factor, is also well-known in everyday experience. For example, a white thread on a black cloth is more easily seen than dark thread on dark cloth. The visibility indicator[1] (Fig. 161) shows contrast conditions ranging from

[1] Developed by Dr. Mathew Luckiesh and Frank K. Moss, Lighting Research Laboratory, General Electric Company.

Visibility and Ease of Seeing are closely related

Visibility increases as the intensity of illumination increases. So does ease of seeing. Read the printed matter below under different intensities of illumination and note the point at which reading becomes difficult or impossible.

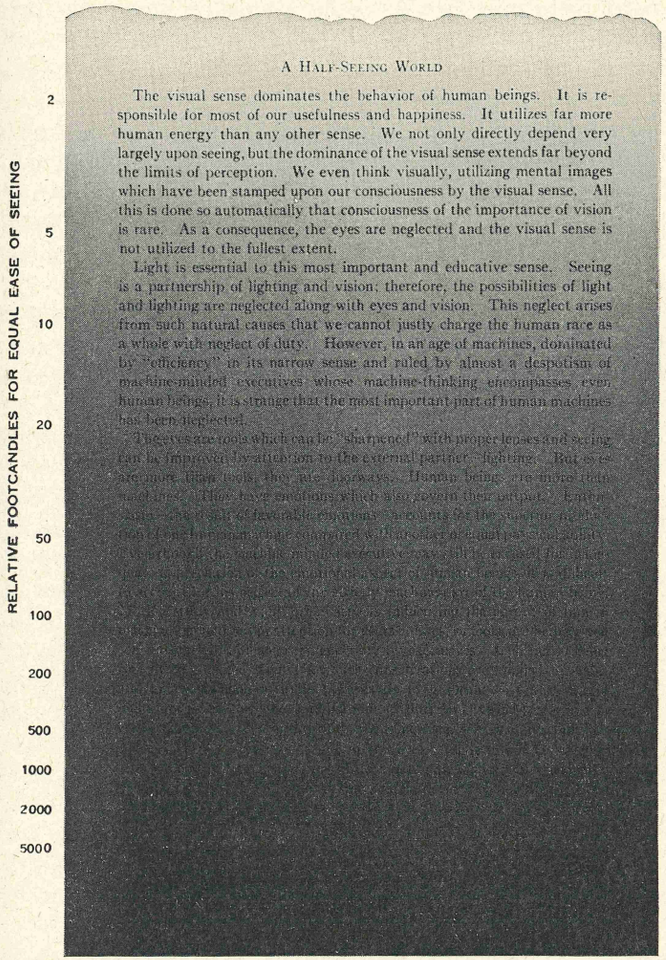


FIG. 161.—The visibility indicator shows that more light is needed to make poor-contrast seeing conditions more visible. (*Transactions of the Illuminating Engineering Society, December*, 1933, *p.* 857.)

black on white to black on black. On the left side of the indicator is a scale of the relative footcandles which must be provided so that any of the contrast conditions can be seen with equal ease. Sufficient light is the only means by which the eyes can see the words and letters at the bottom of the chart where contrast conditions are most severe.

The third factor is time. Many people do not realize that it takes time to see, but this can be effectively demonstrated by rotating a small disk or "seeing spinner" at a constant speed and observing it under a low and a high level of illumination. As the illumination is increased, the disk appears to slow down. Thus, it will be seen that the eye is like a camera in its action, taking snapshots when the illumination is high but requiring time exposures when the illumination is insufficient. This fact is an important one especially where seeing must be rapid, such as in almost every phase of industrial production.

The fourth factor, brightness, is determined to a large degree by the lighting provided on the seeing task. Brightness can be controlled—its desirable level is dictated largely by the other three factors.

Tailoring the Lighting to the Seeing Task.—Many lighting men can remember the day when luminaire outlets were placed on 10- by 10-ft. centers as a general rule. That stage in the evolution of general lighting was a normal result of the conditions then present—a limited selection of equipment, higher lamp costs and energy rates, no general appreciation of the values of higher footcandle levels—in general, the inability comfortably to produce abundant light economically with the equipment then available.

The picture is changed today. Lamp companies have passed on to the customer the manufacturing economies that resulted from increased production, energy rates have sharply reduced (the average rate in the United States is less than 3 cents per kw.-hr., as compared with over 6 cents in 1920), lighting equipment has been developed for almost every type of general and supplementary lighting application, and new, more efficient light sources are available.

The old 10- by 10-ft. spacing rule could have its modern version or rule of thumb in fluorescent lighting as well, but the most satisfactory installations are not made by such methods.

Instead, the lighting is "tailored" to the seeing task, and reflector, light source, spacing, mounting height, etc., are selected to fill most satisfactorily the lighting requirements at hand. Lighting quality, footcandle levels, color quality, and architectural fitness must all be considered in planning a system that will be satisfactory in both a functional and economic sense.

The appraisal of various types of luminaires given in Chap. VI will be found useful in selecting lighting equipment for various types of interiors. Of even more importance, however, is the desirability of becoming so versed with the lighting-comfort factors and desirable footcandle levels that specific luminaires can be intelligently judged for their appropriateness as regards ability to produce those levels economically and at little or no sacrifice in lighting quality and comfort. Simple logic is a most valuable partner to the fluorescent-lighting principles presented in this manual.

Well-shielded vs. Exposed Fluorescent Lamps.—Early fluorescent installations were largely bare lamps mounted on wiring channel attached to the ceiling, because present types of luminaires were not then available. Figure 162 illustrates such an application. Installations of that nature are now branded by some as obsolete and unacceptable, but they were not bad in some instances, for, as shown in Table 22, the maximum tube brightness of fluorecent lamps is of the same order of magnitude as the enclosing globes they replaced, and since the ceiling was brighter and more uniformly lighted by the fluorescent systems, the result was more favorable contrast conditions.[1]

So people have said "Why, bare fluorescent lamps are no brighter than enclosing globes." Such a statement is poor rationalizing, for not only do bare fluorescent lamps present a greater expanse of brightness to the eye but the enclosing globes with which they are compared have not been a part of progressive "lighting for seeing" recommendations for many years. Therefore, those early installations did not represent an "advancement of the theory and practice of illuminating engineering" and could not be termed "progressive." In fact, when made in offices, schools, and other interiors where the seeing task is continuous and the visual requirements exacting, the results were actually bad.

[1] WARD HARRISON, "Fluorescent Luminaires of Today—How Will They Seem in '45?" *Illuminating Engineering*, July, 1941.

It is obvious that conditions are not improved by using bare fluorescent lamps in suspended luminaires. The diffusion characteristics of fluorescent lamps thus make suspended bare-tube luminaires simply elongated enclosing globes, and the cumulative glare effect is likely to be about as great as when bare lamp strips are mounted on the ceiling (because bare lamps in suspended luminaires are more in the field of view). Compared with bare filament lamps, the brightnesses of fluorescent lamps are quite low (Table 22) but they are still high enough to limit indiscriminate methods of application, especially where "lighting for seeing" is the illumination problem.

FIG. 162.—Many early fluorescent installations consisted of bare lamps mounted on the ceiling.

Nevertheless, many of the fluorescent lamps being used in the office and commercial lighting fields are found in bare-lamp types

of equipments. In most of these cases, the fluorescent installation represents an improvement of the footcandle level, and the owner may be extremely enthusiastic about his new system. Yet, topping a recent list of errors found in fluorescent-lighting installations purchased without benefit of engineering advice or planning is the prevalence of "bare tubes that in time become an annoyance to the eyes";[1] so it seems safe to predict that the enthusiasm over such an installation may be a temporary condition especially in offices, drafting rooms, etc., where the visual tasks are severe and prolonged. The customer may even decide in the future that he has paid a high price for an unprogressive lighting system.

As mentioned in Chap. VII, there is little difference from the standpoint of eye comfort between luminaires in which fluorescent lamps are exposed and luminaires that have been poorly designed or have insufficient shielding. In general, for those applications where light is purely a seeing tool (such as in offices), luminaires fail to achieve satisfaction if the lamps are exposed to normal view or if considerable candlepower is directed toward the eye.

It may help in planning "light for work" (industrial, office, schools, drafting rooms, etc.) to remember axiomatically (1) that there is little excuse for low luminaire outputs, (2) to watch out for maintenance, and (3) above all to *watch out for comfort.*

Fluorescent Lighting for Industry.—With plant managers realizing the unreliability of natural daylight, either from side windows or by monitor or saw-tooth building construction, industrial illumination from artificial light has come "into its own." No longer must equipment be positioned and oriented with respect to the direction of natural light, but rather it can be located for maximum efficiency from a manufacturing standpoint. Plants can be built of any size and with as many stories as desired. Several windowless buildings have even been erected.

The fluorescent lamp is almost "a natural" for industrial lighting, for it permits a considerable increase in lighting quality compared with previously available reflectors for general lighting

[1] Emphasizing the fact that one of the considerations that determine the degree to which glare is experienced is the length of time during which the glare source is within the field of vision.

in factories. This advancement is due to the increased size of the light source and to its lower brightness—the result being greater diffusion, less direct and reflected glare, and the absence of harsh, sharp shadows. The relative brightnesses of several filament-lamp industrial-type reflectors is shown in Table 22. The figures indicate the extent of the lighting-quality improvement.

The recommended shielding angle for industrial fluorescent luminaires given in Chap. VI was 15 deg. crosswise with little if any lengthwise. These shielding angles promote good vertical illumination, are easy to meet, and a variety of single and multiple-lamp equipments are now available which appropriately fill the need of this type of service. Some, such as the RLM fluorescent luminaire, have closed ends (which give some endwise shielding—desirable especially in continuous-row installations of low mounting heights), others are open. Porcelain-enamel units without the rigidly closed end construction may be easy to flex and damage the enamel. Of course, it is advantageous to install equipment in which the reflector can be taken down easily for proper cleaning.

Continuous-row Industrial Lighting.—Modern industrial-lighting practice with fluorescent lamps is rapidly standardizing on continuous-row systems running crosswise of the normal viewing direction.[1] This simply means mounting fluorescent industrial reflectors end-to-end below continuous wiring channel. The closed ends of the reflectors act as louvers or baffles in breaking up the brightness effect of a long string of lamps when viewed along the row. The continuous wiring channel, besides carrying all the ballasts, compensators, starters, starter sockets, and lampholders, also serves as the closed wiring trough which requires only one power connection at any convenient point along the row, and simplifies switching as well. The reflectors are easily detachable for proper cleaning.

The continuous rows should be spaced to give around 50 footcandles of illumination, but in this respect the continuous-row system is very flexible. For example, if the footcandle level produced by complete rows of units is not required at present, spaces (omitting every third or fourth reflector) can be left and

[1] W. C. Brown, "Continuous-row Lighting—Now a New Standard for Industry," *Magazine of Light*, No. 5, 1941.

reflectors added later at a low installation expense, because the channel and wiring are already there. Also, reflectors used in the continuous rows can be punched for a third lamp, which when added will inexpensively enable a 50 per cent footcandle increase.[1]

In addition to being flexible, economical, and easy to install and maintain, continuous-row systems have an excellent appearance and improve the visibility of the work, especially those involving polished metallic convex surfaces such as are common on industrial machinery. Several typical continuous-row installations are included in the photographic review found later in this chapter.

General Industrial Lighting by the Conventional Unit Installations.—Many good installations of industrial fluorescent lighting have been made with individual units rather than continuous rows. Perhaps the greatest weakness of such a system, however, is the tendency to replace filament-lamp fixtures by fluorescent luminaires at the same outlets under conditions that give little or no increase in the footcandle level and thus no significant improvement in illumination effectiveness.

For example, assume that a factory area having a Room Index of *D* was lighted to 30 footcandles in service with RLM dome reflectors on 10- by 10-ft. centers, using 300-watt white-bowl filament lamps. An RLM fluorescent luminaire using two 40-watt white fluorescent lamps at each existing outlet would give 20 footcandles in service, a three-lamp unit using 40-watt white lamps would give about 32 footcandles, and a unit using two 100-watt white fluorescent lamps would give about 42 footcandles in service. None of the three provides an in-service level of 50 footcandles representing modern general lighting in industrial areas. On the other hand, 50 footcandles in service can be obtained with continuous rows of two-lamp 40-watt RLM fluorescent luminaires on a 10-ft. spacing.

Several typical layouts were suggested in Chap. VII for the conventional unit-luminaire system. It should always be remembered that, since fluorescent lamps lack any interchangeability of wattage sizes, provisions for future increases in illumination must be provided by installing a flexible layout so that extra luminaires when added later will coordinate with the original installation.

[1] See discussion on page 202.

Generally speaking, fluorescent industrial luminaires are positioned so that the axis of the lamps will be crosswise to the predominant normal viewing direction. Most industrial fluorescent luminaires have their maximum shielding at this direction.

Supplementary Fluorescent Lighting in Industry.—Tailoring the lighting to the specific task often involves the application of specialized or supplementary lighting for localized severe seeing tasks. This is called "supplementary" lighting because it should never be used alone, but should supplement the general lighting system.

The footcandle levels recommended in Chap. VII and the Appendix indicate that there are a good many industrial jobs that should be illuminated with 100 or more footcandles. This usually calls for carefully applied supplementary lighting to illuminate adequately those seeing tasks without causing glare or discomfort to other workers. Care should be taken to prevent excessive brightness contrasts between the local lighted work area and the surroundings. Experience indicates that the brightness contrast should not exceed 10 to 1 within the normal field of view if comfortable lighting is to be secured. Of course, general lighting of the proper quality and quantity helps insure visual comfort in this respect.

In certain instances, the quantity of illumination, or footcandle level, is not the most important factor in the supplementary lighting task. Diffusion, direction, etc., are often equally as important as the footcandle level, and in those instances the problem must be closely studied and the equipment intelligently selected.

Supplementary fluorescent equipment can be broadly classified into concentrating and diffusing categories. The concentrating type is intended to augment the general lighting over certain restricted areas, whereas the diffusing type may also serve as a general lighting system for restricted areas, such as workbenches and inspection tables. The concentrating types are usually made of polished aluminum or Alzak.[1] The diffusing type of supplementary lighting unit is usually quite similar to general lighting luminaires. Another type of diffusing supplementary luminaires is the large-area low-brightness source developed in the course of a study made by the Illuminating Engineering

[1] Trade name of a process developed by the Aluminum Company of America.

Society on lighting for printing plants. Several fluorescent luminaires of this type are available for supplementary lighting applications and are known to provide excellent visibility for the reading of micrometers, cross-feed dials, verniers, etc.

Fluorescent Store Lighting.—It is known that a very large majority of human impressions come through the sense of sight. Actually, every merchant is selling to human eyes. Thus, in addition to providing illumination of the quality and quantity conducive to easy inspection and appraisal of merchandise, the store lighting also has other important functions of display, traffic movement, stimulation, etc.

The chart showing the footcandle levels representative of modern store-lighting practice (Fig. 124) shows the steps in illumination suitable for the different areas in the store. However, besides providing these recommended footcandle levels, it is important that the lighting system accent the features of the merchandise.

Lighting is a prime element in the three A's of merchandising—attraction, atmosphere, and appraisal. The proper brightness pattern is used to capture attention and interest, and it also influences the numbers and kinds of things a customer buys and how often he returns. Attraction lighting means 100 to 150 footcandles on specific displays of high-profit impulse items. If light is used to create an atmosphere of alertness and cheerfulness, to produce a feeling of being in business, and to add accents of interest, people will want to return to that store again and again. And remember that the general over-all brightness of the walls and ceiling is as important as the number of footcandles on the merchandise in producing the effect of a well-lighted store. Higher values of illumination—30, 50, or 100 footcandles at the point and time of sale—promote quick and accurate appraisals by more fully revealing the color, pattern, texture, workmanship, styling, and inherent quality of the merchandise. However, if too great a contrast in illumination levels exists below the showcase or other display lighting and the general illumination, the merchandise may lose its appeal in being brought out of the showcase to the lower footcandle level of general lighting for close inspection.

The luminaire-appraisal tables in Chap. VI illustrate some of the many types of commercial fluorescent equipment now avail-

able. Generally speaking, fluorescent luminaires for store lighting fall into four broad classifications:

1. Foundation lighting—a system providing general illumination only, with any supplementary lighting furnished by other means.

2. Foundation plus—luminaires providing general illumination plus direction of light over selling areas.

3. Luminaires lighting selling areas only—counter and display lighting equipment.

4. Show-window lighting equipment.

In general, there are a considerable number of good equipments now available for store-lighting applications. Recessed, ceiling-mounted, and suspended types of luminaires are all being employed with perhaps a trend toward recessed or close-to-ceiling types and toward continuous lines of light to help direct traffic and give a feeling of spaciousness. The use of adequately shielded fluorescent equipment is also to be desired, and lamps exposed in the normal field of view or poorly shielded are likely to prove a source of dissatisfaction and annoyance before the installation has seen its normal life. Progressive store operators are also likely to confirm the prediction that most lasting satisfaction is likely to result when the lamps themselves are least in evidence. Decorative types of shields and baffles can be used to advantage in stores to relieve the "mechanical" appearance of certain luminaire types.

Diffusing-bottomed fixtures for store lighting should use high-transmitting glass or plastic, producing a high brightness directly beneath the unit (out of the normal field of view) but being more comfortable at wider angles. The common half-cylinder diffusing type of unit is best in long, narrow stores with the luminaire axis in the lengthwise direction of the store. The recommended shielding angles are slightly less for store-lighting luminaires than for office units because people are moving around more and the visual task is not fixed. The decreased shielding, used in such installations, of course, promotes higher luminaire efficiency.

Cove lighting is also regaining prominence in the merchandising field. With two rows, lamps can be overlapped, which makes the dark spaces between lamps appear less noticeable. Two-way coves—some light up and some down—with open top and glass

or louvered bottoms are being successfully used with luminous-sided coves also a good possibility (Fig. 180).

The advantages of fluorescent lamps in store lighting are obvious. These include the comfortable attainment of the higher footcandle levels long desired, cool light, daylight quality, lines of light, low brightness, and appealing color. Although space does not permit a discussion of all the individual seeing tasks and of fluorescent-lighting techniques applicable to individual type of stores, the illustrations included later in this chapter illustrate some of the store-lighting possibilities with fluorescent lamps. Most important is the realization that well-known "lighting for selling" principles apply to fluorescent as well as to filament lighting, that an abundance of comfortable light is a real selling tool, and that the established lighting-quality considerations given in Chap. VI apply to merchandising establishments as well as to offices, factories, etc. Remember also that good general lighting is not enough for the store—specific attraction lighting is needed to provide accents and highlights and produce emphasis and attraction values.

It will usually be best to let the merchant select the color of lamps to be used in his store-lighting installation. Daylight lamps are desirable in some instances, white and soft white in others. It can be pointed out that merchandise to be used outdoors in natural daylight might well be selected under daylight fluorescent lighting, etc. Usually, however, the merchant will want to select the color he considers appropriate for the various portions of his store.

Show-window Lighting.—It is well known that a high brightness, even if seen only out of the side of the eye, attracts the attention of passers-by and causes them to turn and look. Therefore, light is an important factor to the merchant in the creation of attention-compelling show windows. And once the attention has been captured, high illumination of specific merchandise leaves a clear-cut and lasting impression of color, style, and texture. High footcandle levels also minimize annoying daytime reflections in the show-window glass—reflections that veil the merchandise. Truly the show window is the store operator's outside salesman.

Of course, the "three second" selling principles developed for show windows several years ago apply equally as well to fluores-

cent as to filament lighting. These principles include the use of a single idea, silhouette effects, concentration of light, color, and simple background.

The first important step to be taken in the design of a well-lighted show window is the selection of an appropriate footcandle level. Figure 125 graphically indicates the general order of footcandle values for general and feature displays which experience has shown to be effective and practical. The method of designing fluorescent show-window lighting was also discussed in Chap. VII.

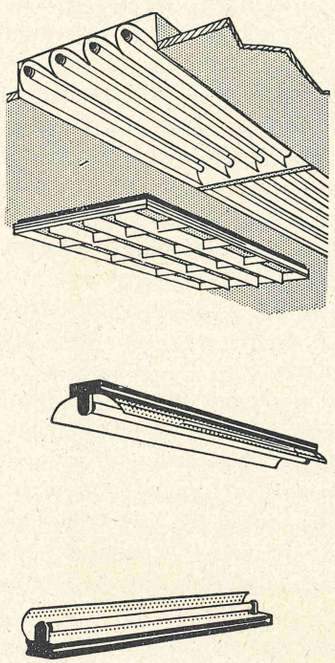


FIG. 163.—Four types of fluorescent equipment commonly used in show-window illumination. From top to bottom: multiple-lamp unit for general show-window lighting; metal louver; single-lamp reflector strip; small reflector strip.

Figure 163 shows four types of fluorescent equipment available for use in the show window. Figure 164 indicates the way such equipments might be located and how they are supplemented by various types of incandescent-filament lamps.

In planning for effective show-window lighting, consider brightness, contrast, color, flexibility, and luminous messages. Large areas of high brightness make the whole show window stand out from its surroundings by minimizing annoying daytime reflections and making the merchandise easy to see and to appraise. As regards contrast, remember that accent lighting or highlighting with clear and tinted spotlights directs the potential customer's eye to specific articles in the display. Fluorescent lamps and color go hand in hand, for colored light at reasonable efficiencies is now available for the first time. Colored fluorescent lamps thus make possible highly dramatic effects without sacrificing the advantages of high brightness. Interest can be stimulated and an idea conveyed by the proper balance of

brightness and color appropriate to the season or the merchandise. Three-, four- or five-color background effects are now practical. Flexibility is important too, for most usable windows need adequate wiring and a sufficient number of extra outlets on the floor and in the upper front part of the window. The

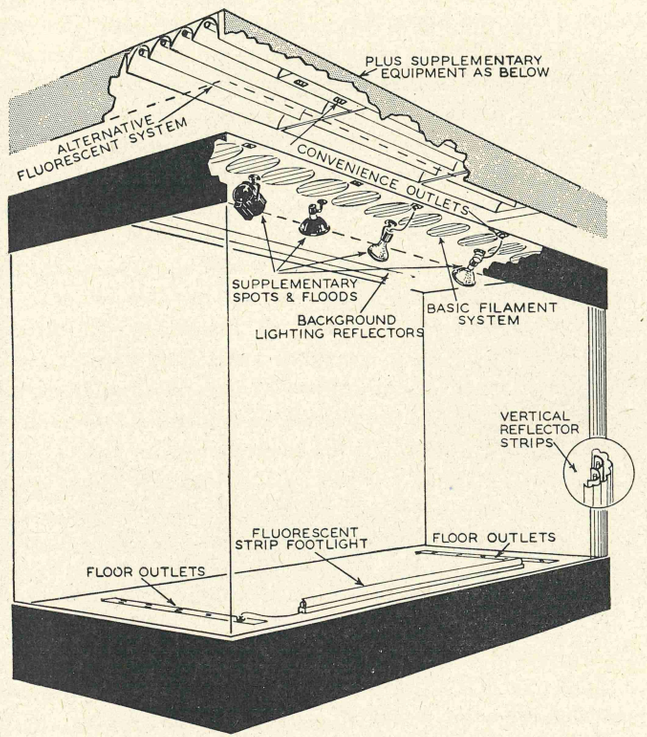


FIG. 164.—Typical locations of various types of fluorescent lighting equipment in the show window.

outlets are for use with the many different types of displays available. Last, but not least—luminous messages. Do not forget that small signs lighted by colored lamps are a valuable feature in many displays.

Among the display tricks being used by modern merchandisers in the show-window lighting field are window markers on the floor, downlighting for background only (to get large area of brightness), accent lighting from concentrating ceiling equipment,

or vertical lighting from sides of show windows (to remove the "flatness" that can easily result if only general lighting is used; vertical lighting from sides also helps get a three-dimensional effect).

Fluorescent lamps also have many excellent applications in modern store-front design.

Fading of Colored Materials.—The extensive use of fluorescent lamps in store lighting, especially for the illumination of wall and floor cases, has raised many questions as to the fading of colored textiles by this new type of light source. An extensive investigation involving over 100 colored specimens revealed the fact that on the average the rate of fading is about equal under tungsten-filament lamp and fluorescent daylight lamps for equal illumination levels. For a particular light source, the amount of fading for a given specimen is approximately proportional to the exposure in footcandle hours, *i.e.*, the product of footcandles and the exposure time. This is true regardless of the source—filament lamps, fluorescent lamps, or natural daylight.

By exposing duplicate specimens to natural daylight, fluorescent daylight lamps, and tungsten-filament lamps (the latter two at 100 footcandles), the following average results were obtained:

	Relative Exposures in Footcandle Hours for Equal Fading
Sunlight plus skylight	1.0
Fluorescent daylight lamps	1.7
Tungsten-filament lamps	1.8

For many materials, fading will become apparent after exposures in the order of 50,000 footcandle hours. This exposure would result whether 100 footcandles were used for 500 hr. or 500 footcandles for 100 hr. The rate of fading will usually be greater for those materials absorbing more of the light falling upon them. For example, most blue specimens would be expected to fade more rapidly under tungsten-filament lamps than under the daylight fluorescent lamp, whereas red and pink would be expected to fade somewhat faster under the daylight fluorescent lamp.

Because of the higher footcandle levels found in fluorescent-lighted wall and floor display cases, it is a good idea to suggest a

suitable schedule for shifting merchandise to avoid fading or gradings in fading. Uniform illumination over the display area solves the latter problem. In any case, it is best to inform the store operator of the fading effect—that some materials fade faster than others—and help him establish a suitable merchandise-shifting schedule. It may also be mentioned that modern high-level lighting helps the merchant to detect and

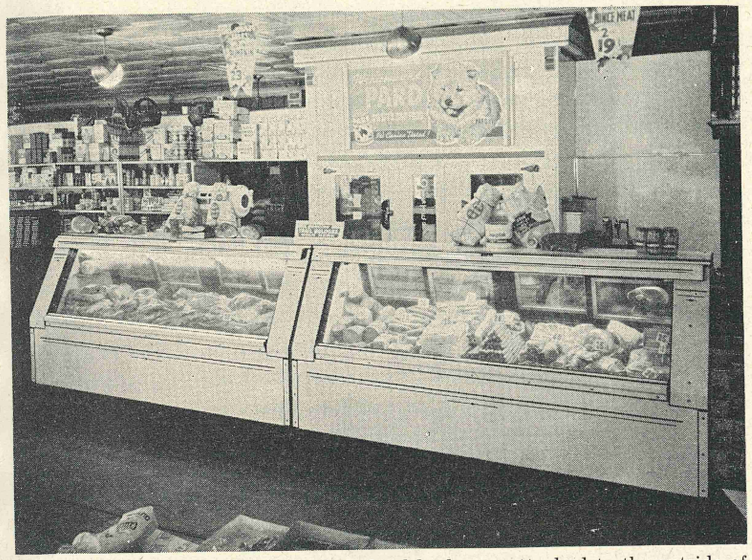


FIG. 165.—The case at the left is lighted by lamps attached to the outside of the case. Notice the resulting veiling reflections from the glass surface. The case at the right is illuminated by fluorescent lamps inside the refrigerated case. Thus reflections are obviated and maximum attraction value achieved.

eliminate items of merchandise that would cause dissatisfaction through early fading in actual service.

Fluorescent Lighting in Refrigerated Display Cases.—The two principal problems encountered in applying fluorescent lighting to refrigerated show cases are (1) starting and (2) color quality. Since temperatures in such display cases average around 36 to 38°F., starting with the ordinary glow-switch starter is usually satisfactory. It has been found that a manually operated starting switch, shunted by a condenser of 0.006 mf. capacity, will also provide reliable starting.[1] A push-button switch con-

[1] See also the discussion on this subject earlier in this manual.

taining the condenser and designed for this particular service is now on the market. The switch should be held closed for about 2 sec. to give adequate cathode preheating before snapping the switch open to start the lamp. A separate starting switch should be installed for each lamp.

Of the sizes commonly employed for showcase lighting, the 15-watt T-8 lamp starts easiest at low ambient temperatures and is recommended for use inside the refrigerated cases. Most favorable starting conditions will be secured by also (1) grounding the reflector to improve starting, and (2) keeping the line voltage preferably within the upper half of the ballast-voltage rating. Although these starting problems could be eliminated by mounting the lamp outside the case, the result would be disconcerting reflections from the glass of the case as shown in Fig. 165.

Since most customer notions regarding satisfactory color appearances of meats and other foods have been based on the lifelong experience of filament-lamp illumination, some criticism may result when daylight or white fluorescent lamps are used in refrigerated showcases of stores having incandescent general lighting. The use of the soft-white lamp will, however, take care of much of this trouble. Also, certain meats will fade or discolor under fluorescent lamps as well as under other sources, and, with modern refrigerated showcase lighting now five to ten times the footcandle level found in older installations, it must be expected that fading will be more serious.[1] Since the greater display value of higher footcandle levels offsets the inconvenience of taking care of this problem, it is suggested that

1. The contents of the case be frequently rearranged.
2. The meats which are the worst offenders be kept farthest from the lamps.
3. The pieces from which cuts are made be rotated so as to present fresh surfaces.

Fluorescent Office Lighting.—There are now many types of well-shielded direct, direct-indirect, and semi-direct fluorescent fixtures that can be used to provide comfortable and adequate fluorescent lighting in the office. Shielding requirements for units of that type are 45 deg. crosswise and 30 deg. lengthwise, appropriate because of the constancy and severity of the visual

[1] See previous discussion of fading.

task and the little need for vertical illumination in the office.

It must be stressed that poorly designed or inadequately shielded luminaire types are scarcely better than bare-lamp luminaires. Optimum office lighting calls for adequate horizontal illumination levels with a minimum of shadows and a maximum of eye comfort. Perhaps the most important attribute of luminaires for office or drafting-room applications is that "they get less bright the farther away you get."

Like industrial lighting, modern fluorescent office illumination is being installed at 50 footcandles or more. Provision should be made in all installations for economical future increases in the footcandle level from the standpoint of wiring capacity, etc.

Much interest is being shown today in the fluorescent troffer for office lighting. Troffer equipment is available in either the recessed or ceiling-mounted type and can be installed in continuous rows as shown in Fig. 188 or individually as seen in Fig. 189. Most troffer equipments have used white porcelain enamel or lacquer as the reflecting surface, but the latest method is to make a trough of a matte aluminum finish (by using the metal or aluminum paint) with parabolic contour, which further increases the comfort in the room by reducing the troffer brightness. In a well-designed troffer, the reflector itself provides a 45-deg. cut-off for the crosswise shielding recommendation and vertical baffles are properly spaced to give about 30 deg. of lengthwise shielding.

A troffer system forms a very convenient means of combining light, sound, and air conditioning. The sound conditioning is secured by using an accoustial ceiling, the troffers simply replacing those of accoustial materials. The air-conditioning load is reduced (per footcandle) because of the relatively high efficiency of troffer systems. Almost any degree of light conditioning from the footcandle standpoint can be secured by properly spacing the troffers, the maintained illumination level ranging from 160 to 230 footcandles when 40-watt fluorescent lamps are used in troffers placed side by side, *i.e.*, entirely covering the ceiling, with a corresponding footcandle reduction when only a fraction of the ceiling is covered. The actual values, of course, depend on the Room Index at hand. Comparable values for the 100-watt lamps are 275 to 375 footcandles.

The ceiling-mounted troffers, of course, save the expense of hanging a false ceiling. However, many customers will be interested in the "light- , air- , and sound-conditioning" possibilities offered by the recessed troffer system.

Luminaires having open-louvered bottoms may be less favorable from a reflected-glare standpoint than equipments employing diffusing glass or plastic panels below the lamp. But even in the case of the open-louvered bottom type of equipment, the reflected brightness of white paper and the like is seldom more than about 150 footlamberts which would not be particularly annoying in a 50-footcandle atmosphere. With higher footcandle levels and therefore less contrast between the reflected brightness of the lamp and the brightness of surroundings, it would simply not be glaring at all. By the same token, bare-lamp luminaires would be acceptable as regards reflected glare in atmospheres of 50 footcandles or more, but on direct-glare basis they are less satisfactory and may in time even prove annoying, as has been previously mentioned.

While speaking of comfortable brightness contrast, it is well to point out that at higher illumination levels disturbing contrasts can exist between dark desk tops and white paper and other light material used on the desk. A comparison of Figs. 166 and 167 shows how this problem can be solved by the use of lighter desk tops to minimize the brightness contrast mentioned.

Little has been said about fluorescent indirect lighting because such luminaires have not been widely used up to the present. Although relatively inefficient and more expensive, fluorescent indirect luminaires can give a "coffer" effect, and the system may be comfortable at illumination levels exceeding 50 footcandles—approximately the comfort limit of filament indirect lighting because of the ceiling brightness. Direct-indirect units are less expensive and more efficient. They can do an excellent illumination job if the louvers and luminaire sides are not too bright, although at 50 footcandles or more, many fixtures must be used. Recessed or ceiling-mounted equipments can be selected to overcome the "forest of fixtures" some customers object to.

Drafting-room Lighting.—When the drafting tables are nearly vertical, they may be very satisfactorily illuminated by the use of troffers as shown in Fig. 191. However, if the boards are horizontal or nearly horizontal, the reflections from shiny draft-

FIG. 166.—With higher levels of illumination, contrasts between dark desk tops and white paper become more annoying.

FIG. 167.—The solution is the use of lighter desk tops. Not only do the secretaries appreciate the consideration for their eyes (by minimizing brightness contrast) but the general appearance of the office is improved.

ing instruments strike the eye and produce a serious reflected-glare problem. Too, the draftman's body or his instruments are more likely to cast shadows on the horizontal boards which interfere with seeing.

Figure 192 shows one solution to most of these problems. The troffers are made of diffuse aluminum and are recessed in the ceiling at a diagonal angle of 45 deg. to the axis of the room. The bottoms of the troffers are louvered to provide shielding from direct glare, and because of their diagonal location, objectionable shadows are practically eliminated.[1] Not only is the reflected glare minimized because of the high footcandle level on the drafting board (nearly 100 footcandles in this case) but because of the angle at which the troffers are located bright reflections are more easily escaped by a slight natural movement of the head. Of course, the problem could also be solved by turning flat drafting tables at an angle to the lamp axis.

Fluorescent Lighting in the Home.—There are several excellent applications for fluorescent lamps in the home, especially for the lighting of bathroom mirrors, work areas underneath kitchen cabinets, laundry trays where usually the 1½-in. diameter lamps can be exposed. In most other places in the home, the lamps should be well shielded. Fluorescent lamps can often be applied for the lighting of low-ceilinged recreation rooms, where conventional filament-lamp equipments hang too low. In fact, the ceilings of most rooms in the home are low (7 ft. 1 in. to about 9 ft.) and people do not like "things that hang down." The new sources are easily adapted to coves and valance lighting found in many modern homes.

Several of the photographs (Figs. 194 to 199) in the photographic review found later in this chapter show how fluorescent lamps can be advantageously employed in the home. However, fluorescent applications must be in keeping with the decorative theme if they are to remain satisfactory for years to come. Some suspended, ceiling-mounted, and portable fluorescent units are available for home use. Among the portable fluorescent equipments are the large three-lite I.E.S. type lamp using two 14-watt fluorescent lamps in series below the diffusing bowl instead of

[1] Except when using the 45-deg. triangle, which is only a small percentage of the work.

the familiar candelabra and the floor units using three or four short fluorescent lamps without a diffusing bowl.

Good home lighting has three objectives: (1) to produce a homelike atmosphere or "domestic feeling," (2) to provide eyesight comfort and conservation, and (3) to have decorative fitness with the rest of the home. It is likely that in the future fluorescent equipments will be more generally available to meet these objectives.

Miscellaneous Applications.—It has been the purpose of this chapter to discuss briefly some of the important aspects of fluorescent lighting for seeing, selling, and production. In addition to these three principal divisions of illumination work, there are several miscellaneous fluorescent applications that are worthy of brief mention. Obviously, it is impossible to consider all the specific illumination fields in which fluorescent lamps have found application. It is hoped, however, that the principles given in this manual, together with ideas gleaned from illustrations and through individual ingenuity and resourcefulness, will point the way to unlimited ability as regards diversity of applications.

In the Theater.—Fluorescent lamps have much to offer the theater operator in the form of (1) abundant color and high luminous efficiency for attraction and atmosphere, (2) flexibility, (3) a convenient shape to fit architectural features of theaters, and (4) cool light. Many applications have been made in theater fronts, lobbies, attraction-letter panels, etc. The possibilities for fluorescent coves, niches, free-standing displays, signs, etc., seem almost unlimited.

Photographic Applications.—Because of their low brightness and less radiant heat, fluorescent lamps are an ideal light source for photography. The daylight lamp is an efficient lamp to supplement natural daylight.[1] Employed alone, fluorescent daylight lamps give excellent rendition with both panchromatic and orthochromatic portrait films, and, in addition, harsh concentrating shadows are often avoided, reducing the amount of retouching necessary to remove eye squinting. The blue lamp may be used advantageously in special photographic applica-

[1] The film speed for natural daylight should be used for daylight fluorescent lighting. These daylight film speeds are, in general, about 50 per cent faster than the tungsten-lamp speeds.

tions and for enlarging because nearly all the light from this source is in the blue-violet region where ordinary emulsions are sensitive. Figure 202 shows a typical photographic studio employing fluorescent lighting.

Museums and Galleries.—Lighting quality and color quality are as important in the museum and gallery as for critical inspection processes in industry, and great care usually must be exercised in providing the best display and appraisal lighting conditions possible. Figure 203 shows a gallery for the display of modern art which is fittingly lighted with daylight fluorescent lamps located in trough reflectors mounted at the ceiling. The color quality and coolness of this light source are obvious advantages for applications of this nature.

Fluorescent Floodlighting.—Figure 204 shows a floodlight developed primarily for creating many of the beautiful colored effects at the Golden Gate International Exposition. Fluorescent-floodlighting units of this type are now being used for the lighting of buildings, gardens, amusement parks, roadside stands, and other outdoor displays and festivals. Figure 205 shows a novel fluorescent-floodlighting treatment on a building front in which two rows of 30-watt white fluorescent lamps are used in each of the four silhouette troughs running up the front of the red-brick building.

Photographic Review of Fluorescent Installations.—Because an illustration of a good fluorescent installation is so much more valuable than words in describing the applications of fluorescent lamps to that particular type of interior, the following pages contain a photographic review of some outstanding recent installations. Accompanying each illustration will be found the essential engineering data which indicate how that specific problem was solved. The information may show how similar tasks can be illuminated.

It has been prophesied that lighting equipment of the future will for the most part be integral with the building which it illuminates and that footcandle standards will be higher than are common today. If history reveals such a prediction to have been true, certainly it will mean that lighting engineers will serve an important function in tomorrow's building methods. It will also open up new vistas in planning and executing lighting designs.

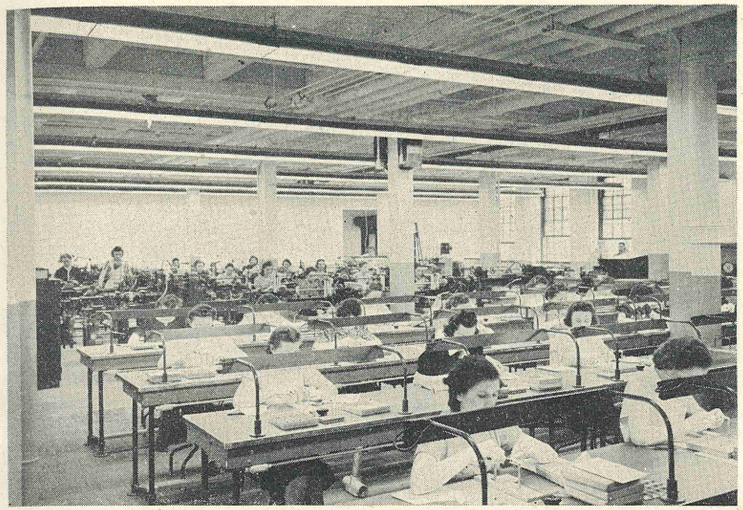


FIG. 168.—Continuous rows of RLM fluorescent luminaires using 40-watt white fluorescent lamps provide 40 footcandles in service of general lighting in this factory area. The units are mounted 10 ft. 8 in. above the floor and the spacing between rows is 10 ft. 8 in. There is a reflector (with two 40-watt lamps) for every 47 sq. ft. of floor area. Individual bench units in the foreground supply over 200 footcandles of supplementary illumination for the more critical seeing tasks performed there.

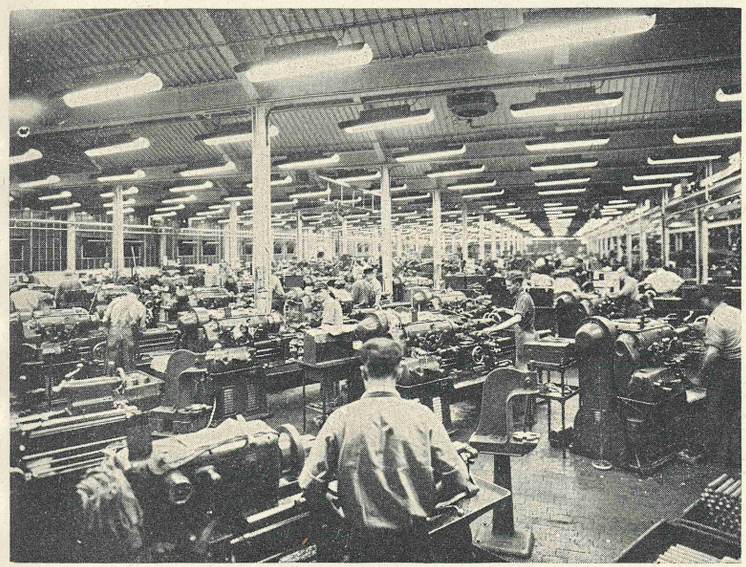


FIG. 169.—This industrial area is lighted with two-lamp RF units on 10 × 10 foot spacings with 12½- and 13-ft. mounting heights. Forty footcandles are provided in service.

FIG. 170.—This newspaper composing room is lighted with fluorescent units on 8-ft. centers mounted 12 ft. high. Two 100-watt lamps are used in each reflector. The illumination level is 70 footcandles in service.

FIG. 171.—A canning department lighted with 576 fluorescent luminaires each employing two 40-watt daylight lamps. The units are 11 ft. 7 in. above the floor and the rows are 10 ft. apart.

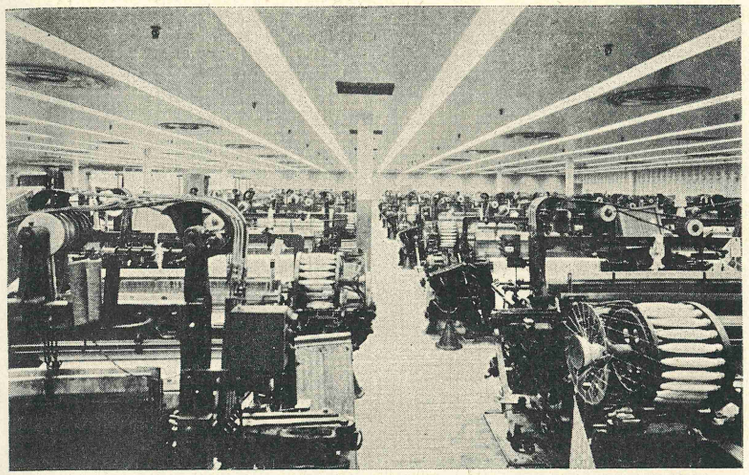


FIG. 172.—In this air-conditioned textile plant fluorescent troffers are used on 5 ft. 4 in. centers to provide 60 footcandles in service.

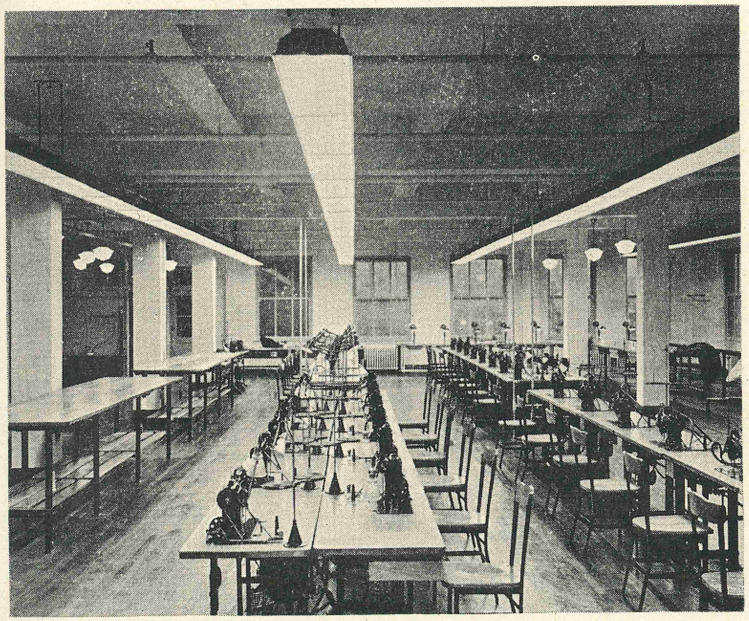


FIG. 173.—Continuous rows of RLM luminaires each employing two 40-watt fluorescent lamps are used to provide 60 footcandles of illumination in the workroom of this large metropolitan store. The rows are 8 ft. apart.

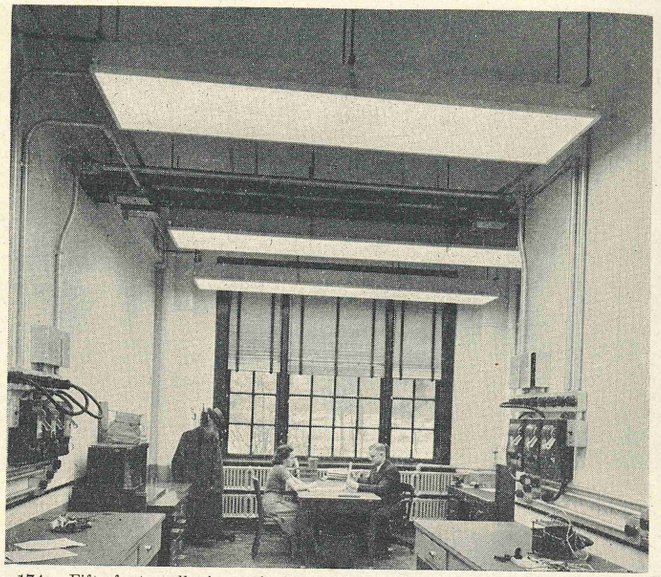


FIG. 174.—Fifty footcandles in service are produced by twin troffers 6 ft. apart (equivalent to rows of lamps on 3-ft. centers) in this industrial laboratory. The units are suspended from the ceiling.

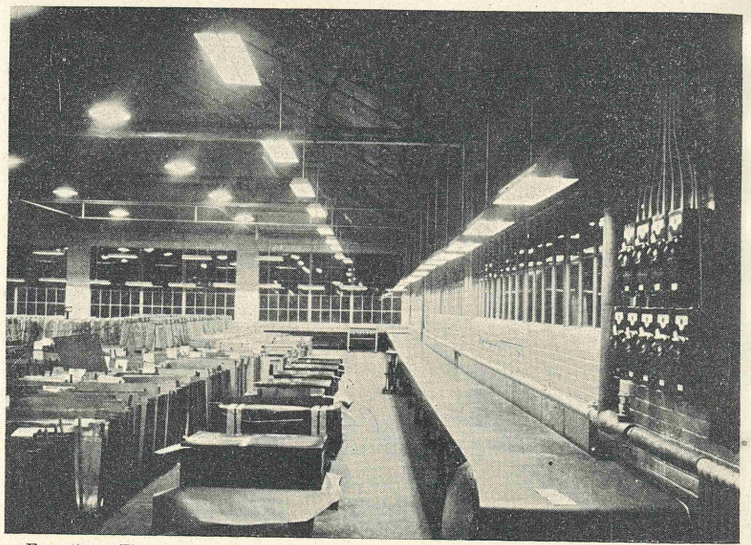


FIG. 175.—Fluorescent lighting has proved very beneficial for the lighting of tinplate inspection processes. The low-brightness source cuts down obscuring sheen, minimizing eye fatigue.

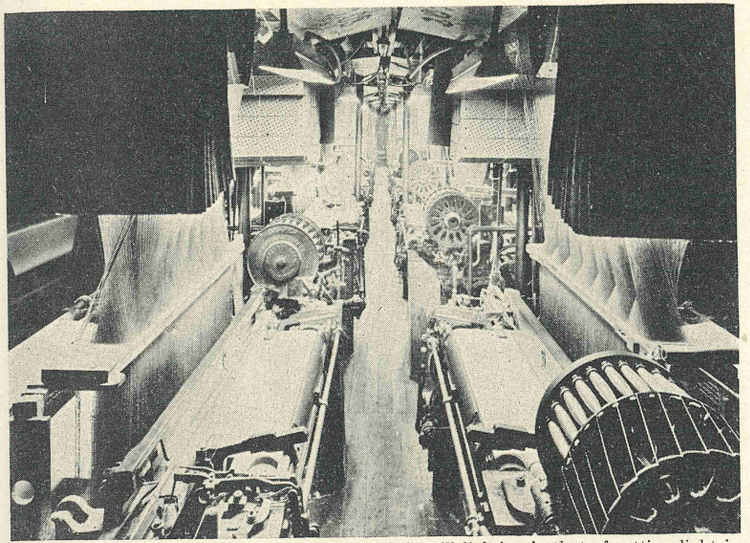


FIG. 176.—One of the tough problems in textile-mill lighting is that of getting light in and around all of the intricate parts of a jacquard loom. Here is a battery of those looms lighted with fluorescent lamps. The elongated source minimizes confusing shadows.

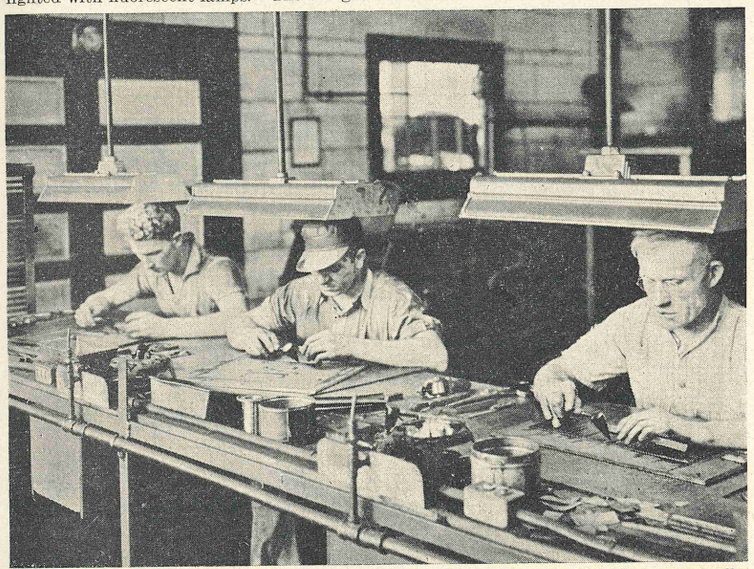


FIG. 177.—All studies of requirements for bench work and fine assembly indicate generally a need for supplementary diffusing sources. Shadows are thus softened and contrast (due to glint from shiny parts) is minimized. Each unit can be mounted overhead out of the way of the worker without causing discomfort due to heat. Illumination of 100 or more footcandles may be provided.

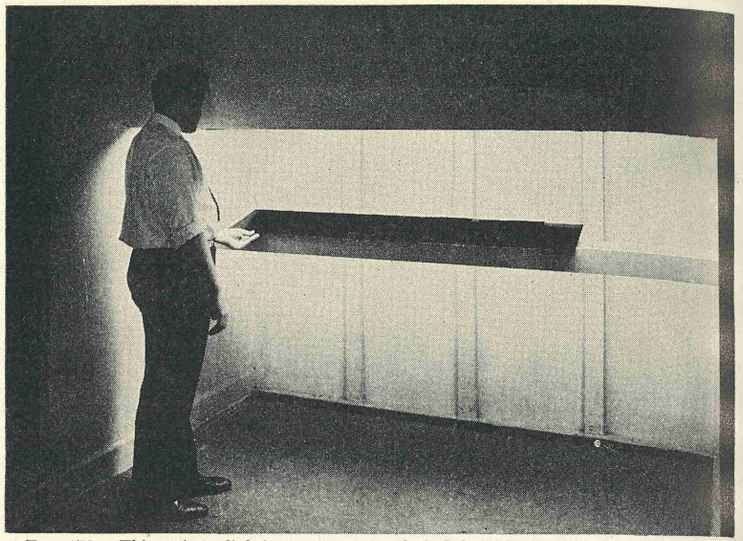


FIG. 178.—This unique lighting system was designed to check the color matching of lacquers and baked enamel samples against standards. A total of twenty-four 30-watt daylight lamps and twelve 15-watt daylight lamps are arranged in a bank made up of 12 parallel rows of lamps. The system is switched on three circuits so that illumination levels of approximately 175, 350, and 500 footcandles are available. The illumination is quite uniform at the bench on which the color comparisons are made and the booth is so designed that when the inspector stands fairly close to the shield the direct view of the light source itself is cut off.

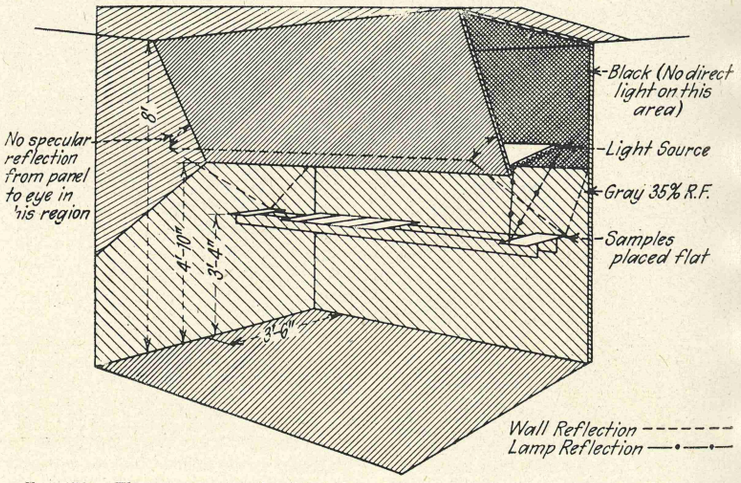


FIG. 179.—The construction details of the color-matching booth described in Fig. 178.

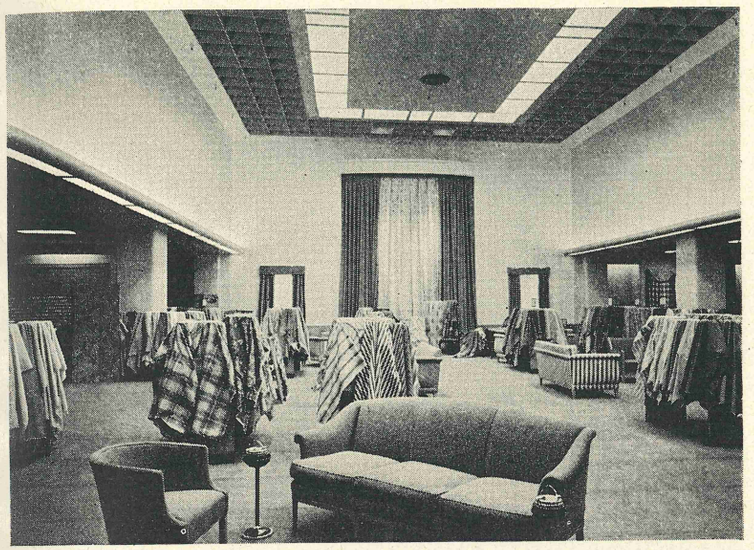


FIG. 180.—Large louvers for the skylight and built-in louvered fluorescent lighting are combined as an integral ceiling pattern in this large middle-western department store. Two continuous rows of white fluorescent lamps in the "up and down" cove with luminous soffit produce desirable wall and ceiling brightness. The two rows are staggered as shown in the sketch. Six-lamp closed-top, louvered-bottom luminaires incorporated as an integral part of the architectural treatment provide an interesting ceiling pattern and furnish most of the illumination on the merchandise.

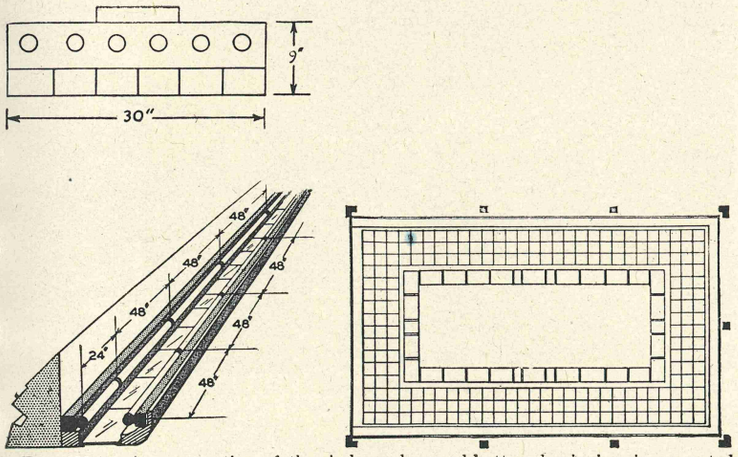


FIG. 180A.—A cross section of the six-lamp louvered-bottom luminaires incorporated as an interesting part of the ceiling. Lower left, staggered white fluorescent lamps in an "up and down" cove. Lower right, the ceiling pattern.

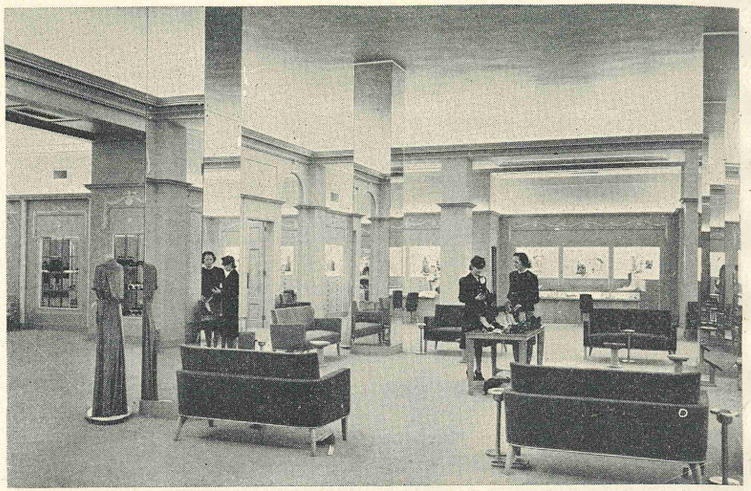


FIG. 181.—This fashionable women's-clothing store is appropriately lighted with soft and shadow-free illumination from fluorescent coves employing 40-watt lamps. The view also illustrates the unusual effect created by the column mirrors.

FIG. 182.—This outstanding jewelry store installation consists of ceiling-mounted fluorescent lamps supplemented by filament downlighting to build up the illumination on the diamond and silverware displays. The illumination level in service is of the order of 100 footcandles on the counter tops throughout the store and in this atmosphere the brightness of the lamps does not seem objectionable. Too, baffles are used on 2-ft. centers to prevent any extended lengthwise viewing along the rows.

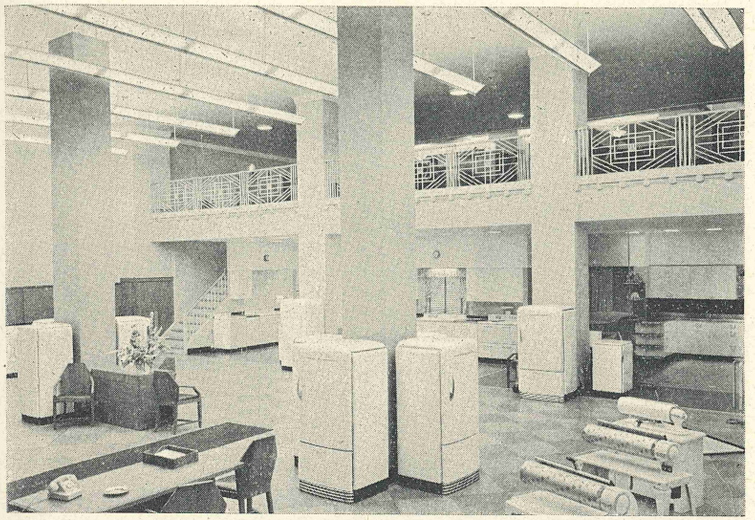


FIG. 183.—An illumination level of 80 footcandles in service is produced by this store-lighting installation. The system is distinctive because of the close control of brightness contrasts. The brightness of the luminaires themselves is of the order of 2½ times the average brightness of the ceiling directly above the units, 3.7 times the average brightness of the ceiling between the rows, and only about 8 times the brightness of the appliances.

FIG. 184.—Individually located recessed troffers are used in this drugstore to produce an illumination level of 35 footcandles in service. Spacings average 4 ft. 5 in. on centers laterally, and 3 ft. 6 in. end-to-end. Forty-watt fluorescent lamps are employed.

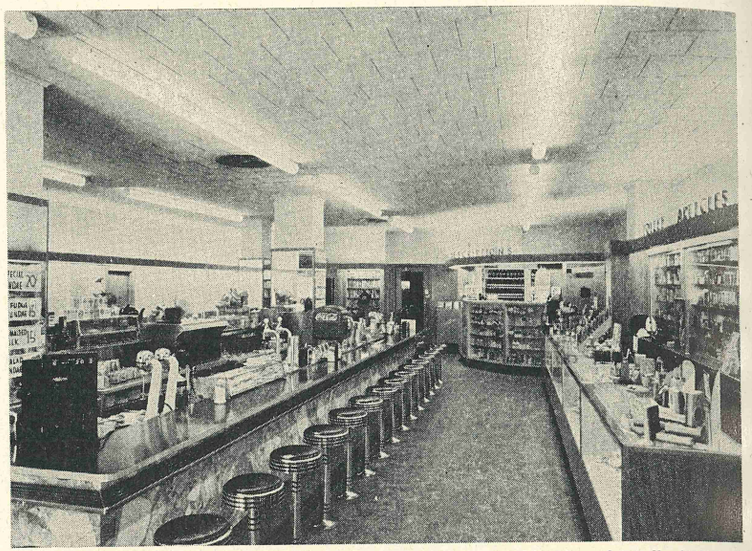


FIG. 185.—This neighborhood drugstore is lighted by a combination of totally indirect silvered-bowl filament units and recessed asymmetrical trough reflectors over the counters. Sixty-five footcandles are provided on the counter tops from the 40-watt white fluorescent system.

FIG. 186.—Illumination is provided in this drugstore by ceiling-mounted fluorescent lamps shielded by circular louvers on close spacing and by "up and down" coves seen along the wall.

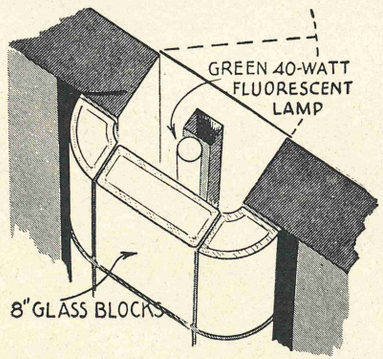


FIG. 187.—This old building was brought to life by installing four columns of glass blocks lighted from within by 40-watt green fluorescent lamps.

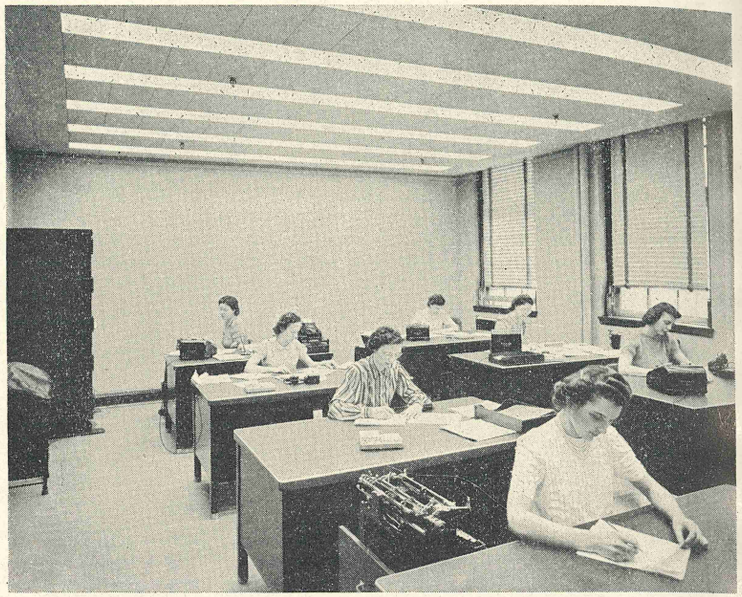


FIG. 188.—A business office lighted to 50 footcandles by continuous rows of white 40-watt fluorescent lamps in recessed troffers on 3-ft. centers.

FIG. 189.—An office-lighting installation consisting of individually located fluorescent troffers. Note how the units near the rear of the room seem to "fade out." Thus, this installation achieves one of the real attributes of good office lighting.

FIG. 190.—Office lighting by suspended direct-indirect luminaires each employing six 40-watt fluorescent lamps. The top of the luminaire is open and the bottom has egg-crate louvers. Fifty footcandles are maintained in service.

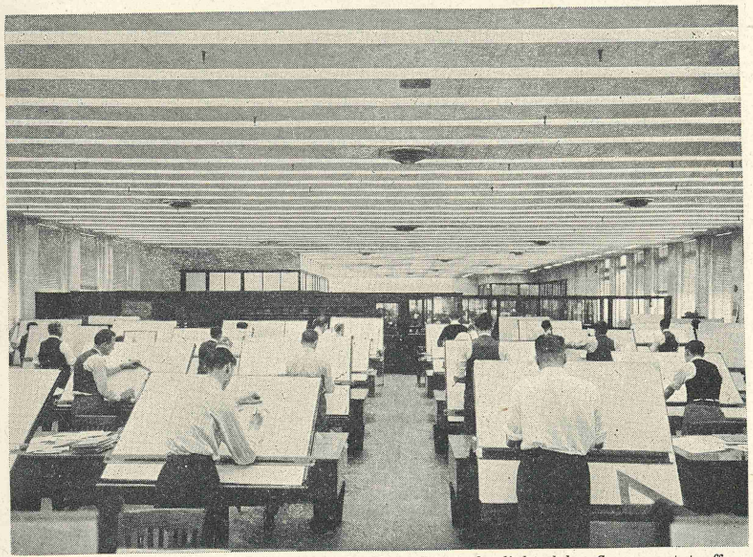


FIG. 191.—Substantially vertical drawing boards can be lighted by fluorescent troffers mounted crosswise to the normal view in the conventional manner. In this installation, the troffers are on 3-ft. centers.

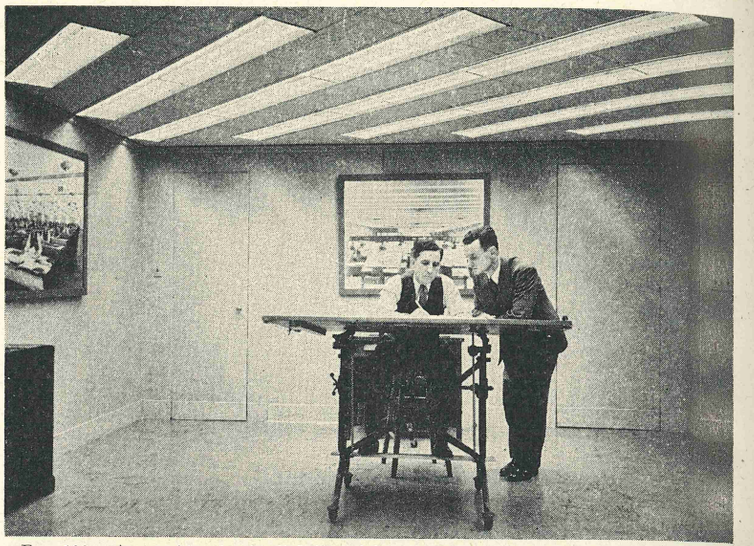


FIG. 192.—A new idea in the lighting of horizontal drafting boards is shown in this installation. The diffuse aluminum troffers are recessed in the ceiling at an angle of 45 deg. with the axis of the room (and so with the axis of the board).

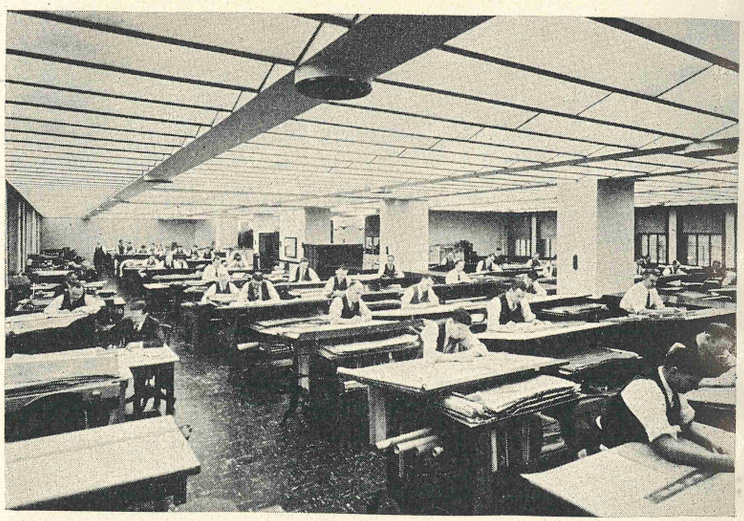
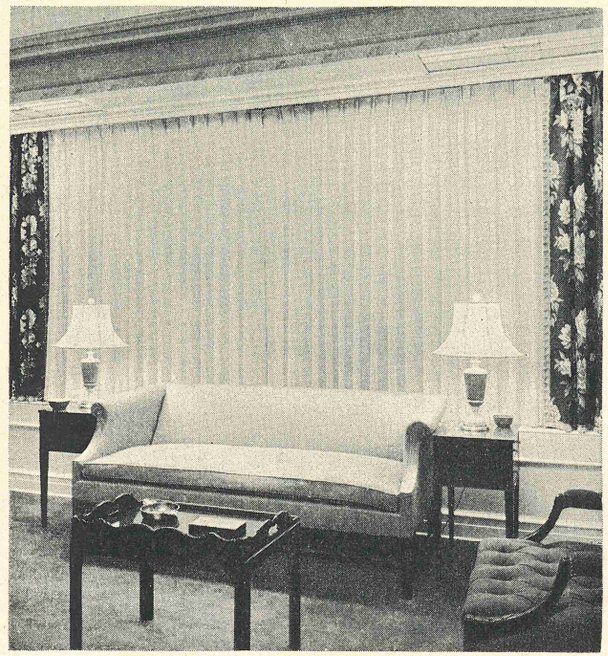


FIG. 193.—An outstanding fluorescent-lighting system in a drafting room is shown here. The ceiling is entirely covered with a saw-tooth arrangement of alternate tilted panels of slightly etched, clear window glass and acoustical material. The light sources are 36-in. daylight fluorescent lamps. The system provides an average of 85 footcandles of exceedingly high-quality illumination. The draftsmen all face in the same direction and at normal viewing angles do not see the glass panels which, however, are not uncomfortably bright even when one looks directly at them.



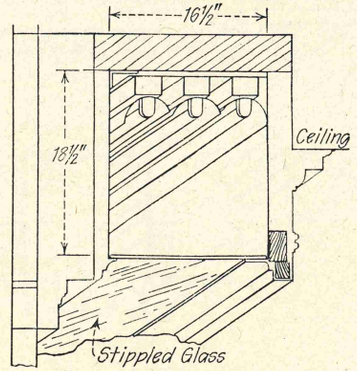
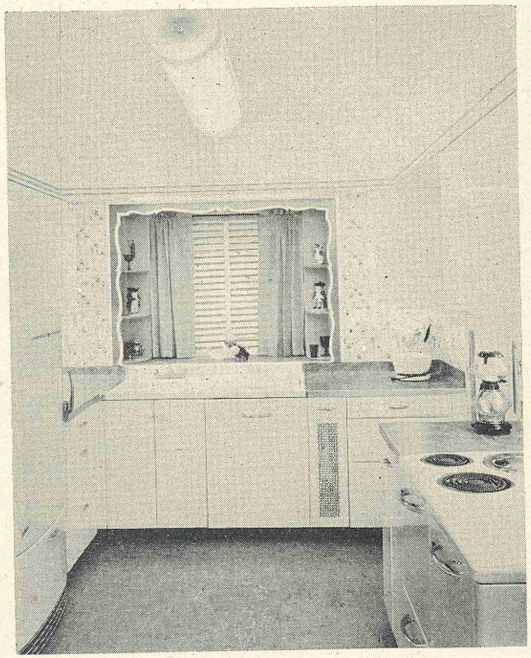


FIG. 194.—One way in which fluorescent lighting can be used in the living room of the home. Finely stippled crystal-glass paneling in the soffit over the bay window conceals three parallel rows of 40-watt soft white fluorescent lamps, each row mounted in a metal reflector. The three rows may be operated singly or all together, to produce 30 to 35 footcandles on the reading plane even with the table lamps unlighted.



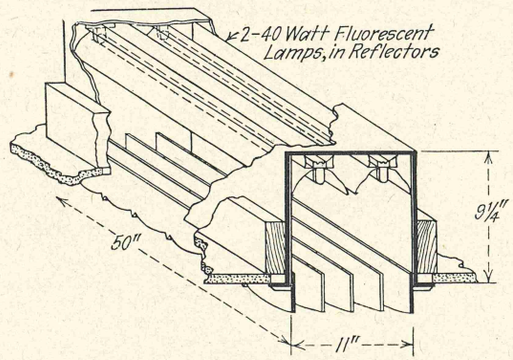
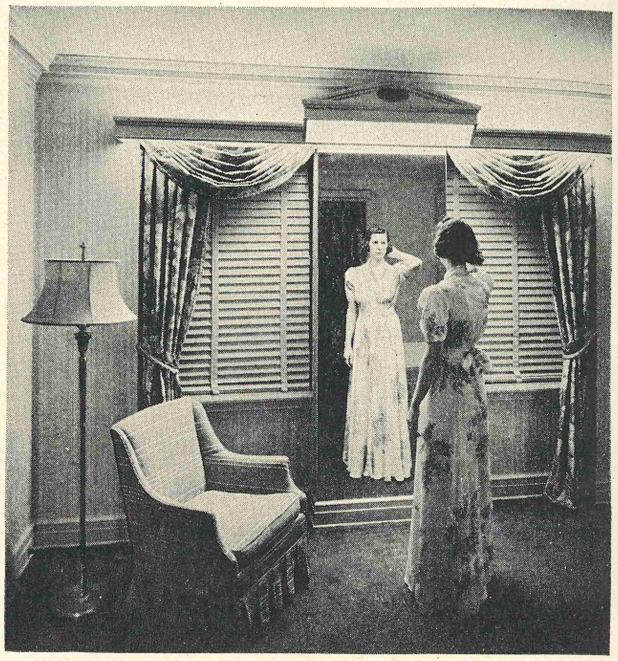


FIG. 195.—This kitchen fixture consists of two 40-watt lamps enclosed in a sheet of white translucent plastic material which fits into etched glass end pieces. Despite its actual size, the fixture so effectively blends into the ceiling that its size is not objectionable. Two 40-watt daylight fluorescent lamps are mounted parallel to the soffit over the sink, each with a reflector to direct the light downward. Scalloped painted louvers shield the lamps.

FIG. 196.—Fifty to sixty footcandles of illumination are provided on this range top by the use of a single 40-watt daylight fluorescent lamp. The wiring channel is recessed to the level of the wall and a plastic shield over the lamp keeps it from being visible from across the room.



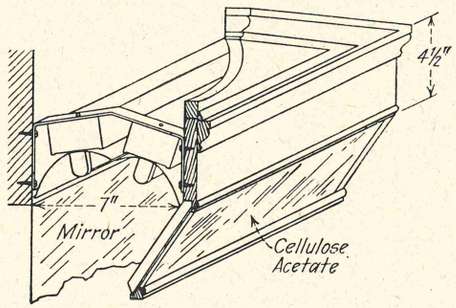
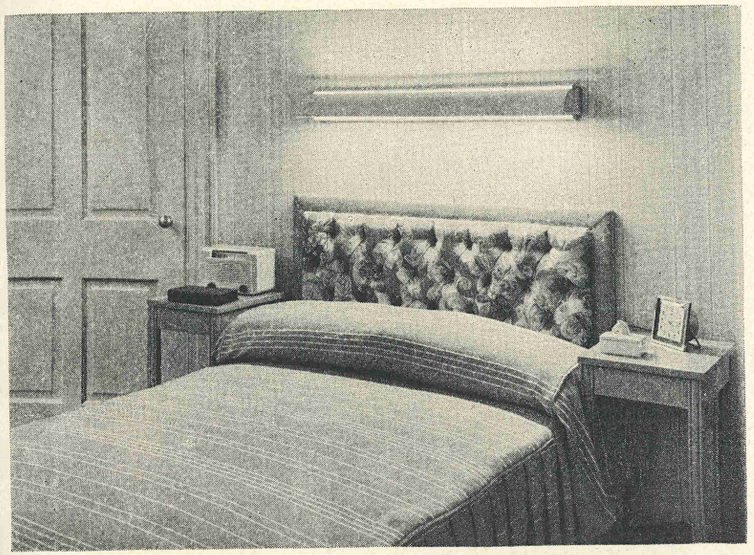


FIG. 197.—By careful design and placement of reflectors over full-length mirrors, glareless illumination of 20 to 25 footcandles can be secured from head to foot at a distance of 30 inches from the mirror. In this case, two 30-watt white fluorescent lamps are used for the mirror and one for each decorative window valance.



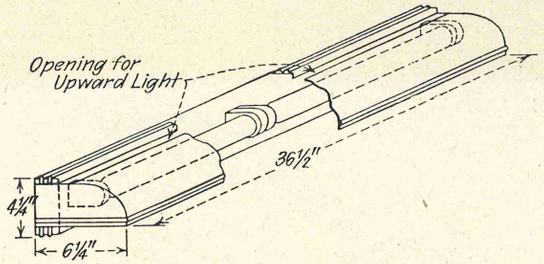


FIG. 198.—Fluorescent lamps can also be used in bed-lamp units. This custom-built fixture is about 37 in. long and houses two 15-watt fluorescent lamps placed end to end. The fixture can be painted to match the woodwork and it produces 30 to 40 footcandles at the reading position. Four narrow openings running the entire length of the fixture allow a little upward light.

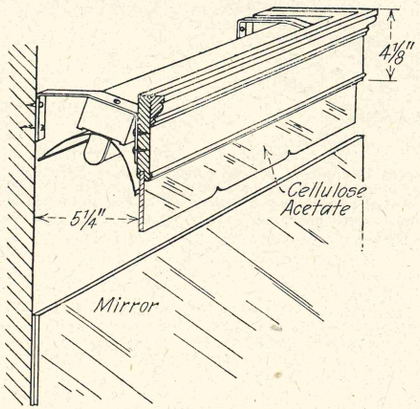


FIG. 199.—The use of fluorescent lamps above the dressing table. In this case one 30-watt lamp is mounted in a metal channel over which a reflector directs the light downward. Twenty to twenty-five footcandles result.

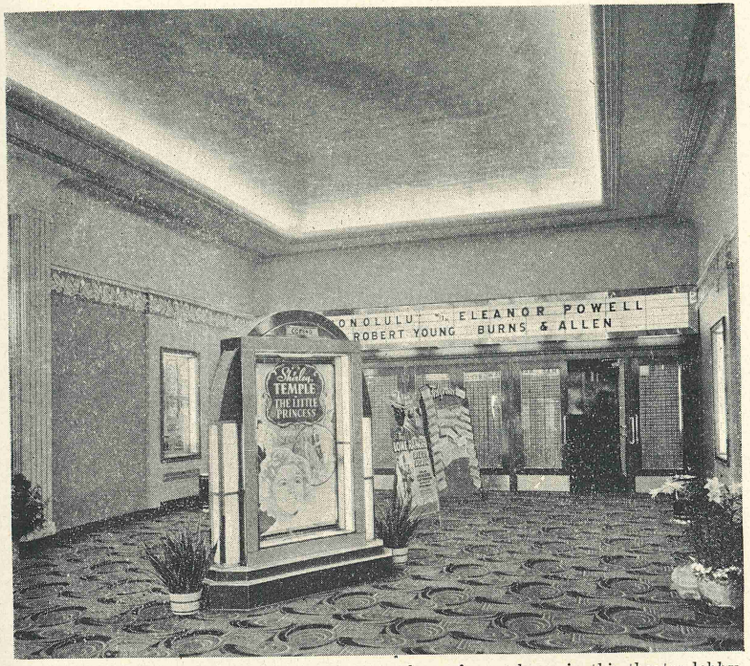


FIG. 200.—Unusual lighting creates an atmosphere of rare charm in this theater lobby. Blue fluorescent lamps light the rectangular ceiling cove, pink and gold fluorescent lamps are used in the luminous signs over the doors at each end, and daylight fluorescent lamps supply supplementary lighting for the recessed poster niches and the free-standing display.

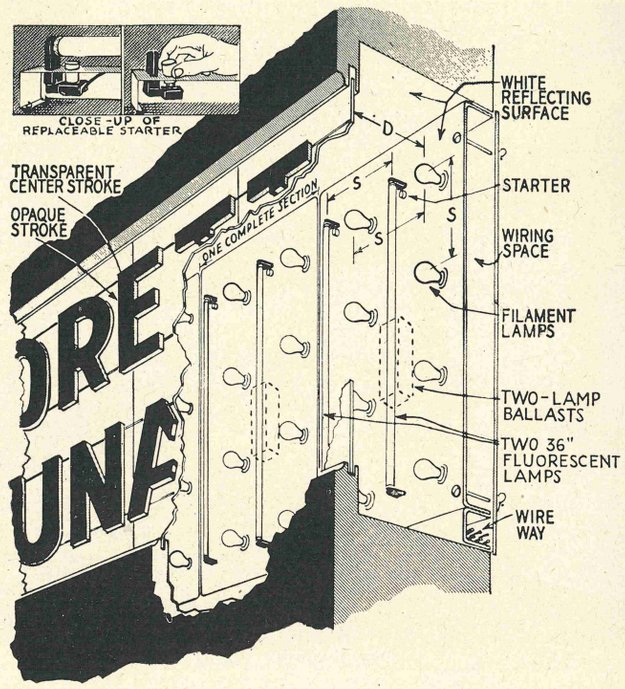


FIG. 201.—A combination filament and fluorescent letter sign which provides both color and flashing action. The fluorescent lamps are burned continuously—the filament lamps are flashed. The letters can be selected to have one color when the fluorescent is on alone, and another color when the filament lamps come on.

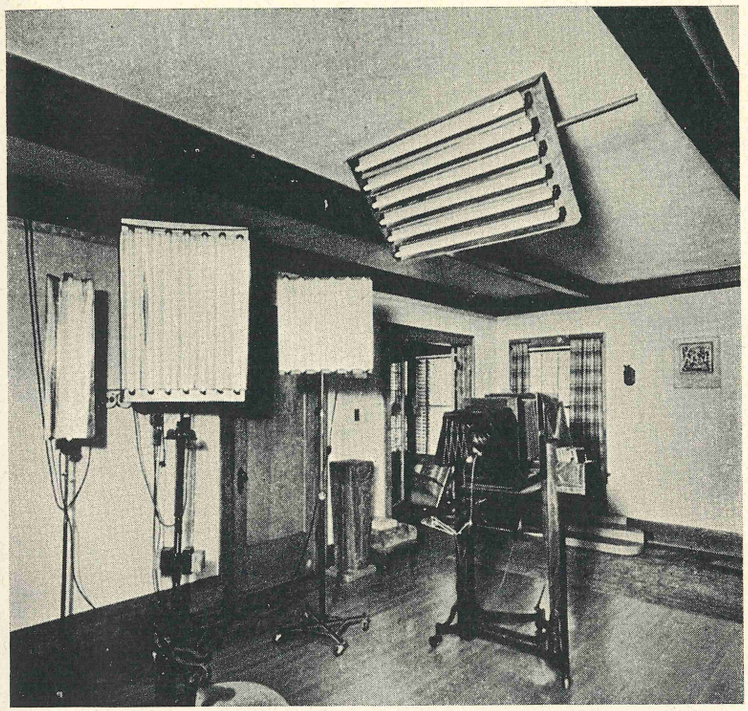


FIG. 202.—Coolness and freedom from disturbing glare make the fluorescent lamp ideal for many photograph applications. Too harsh concentrating shadows are often avoided, thus reducing the amount of retouching frequently necessary to remove eye squinting. Daylight fluorescent lamps are also being used for color photography.

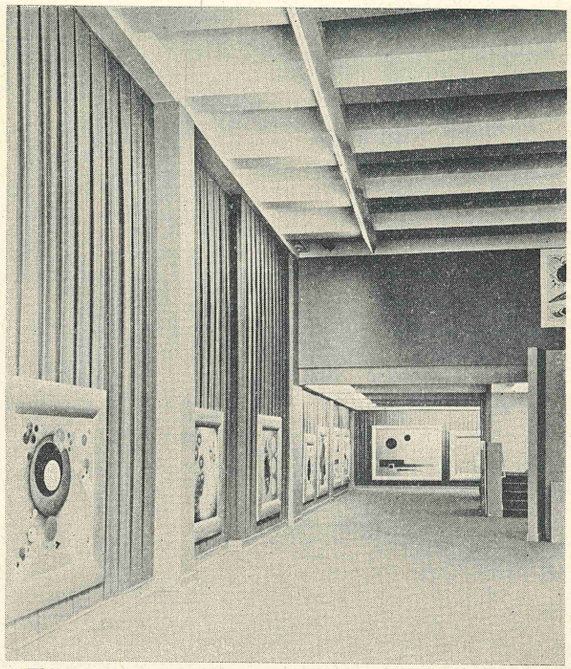


FIG. 203.—This gallery for the display of modern art is fittingly lighted with daylight fluorescent lamps. The illumination at picture level is approximately 40 footcandles and on a horizontal plane in the center of the room 10 footcandles.

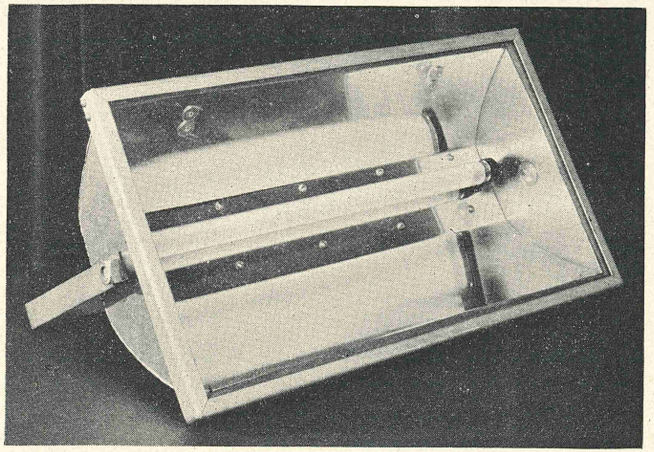


FIG. 204.—A floodlighting unit especially designed for fluorescent lamps in outdoor applications.

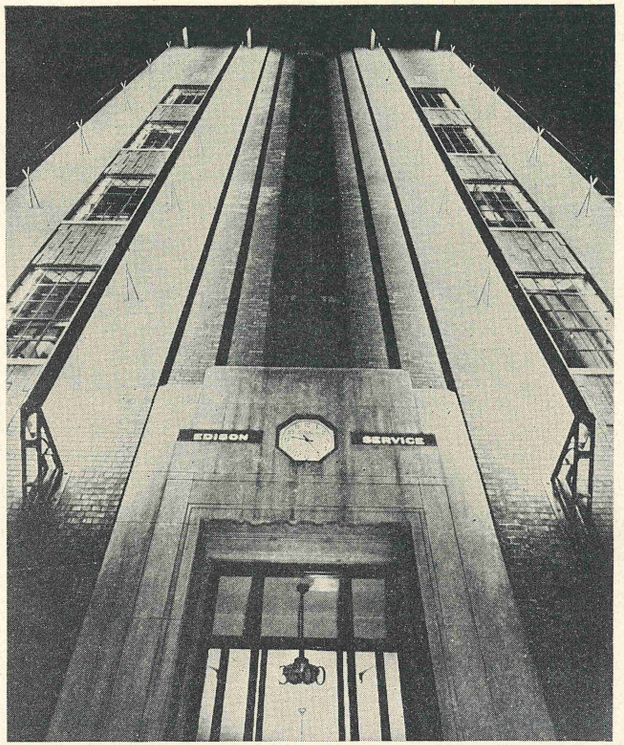


FIG. 205.—A novel floodlighting job. This building front is illuminated by fluorescent lamps in four channels held out a short distance from the building.

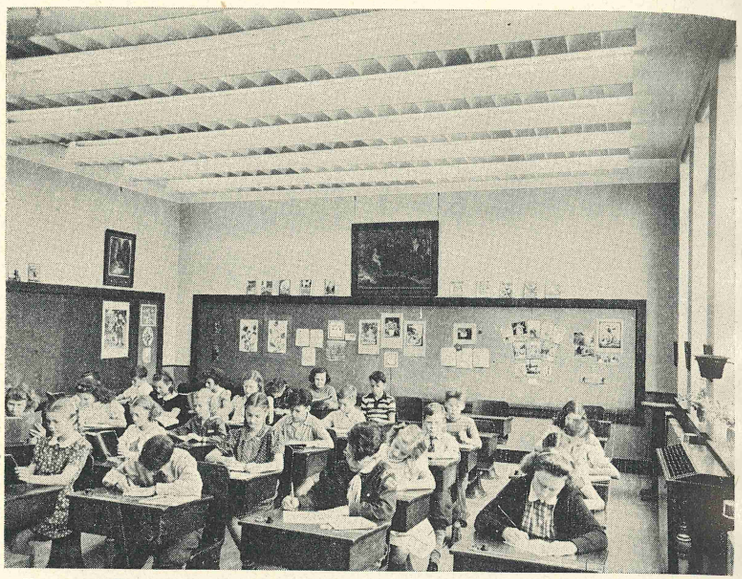


FIG. 206.—This public-school classroom is lighted by forty-eight 40-watt daylight fluorescent lamps in a variation of the troffer which gives good shielding and a relatively uniform ceiling brightness. The illumination level is 50 footcandles.

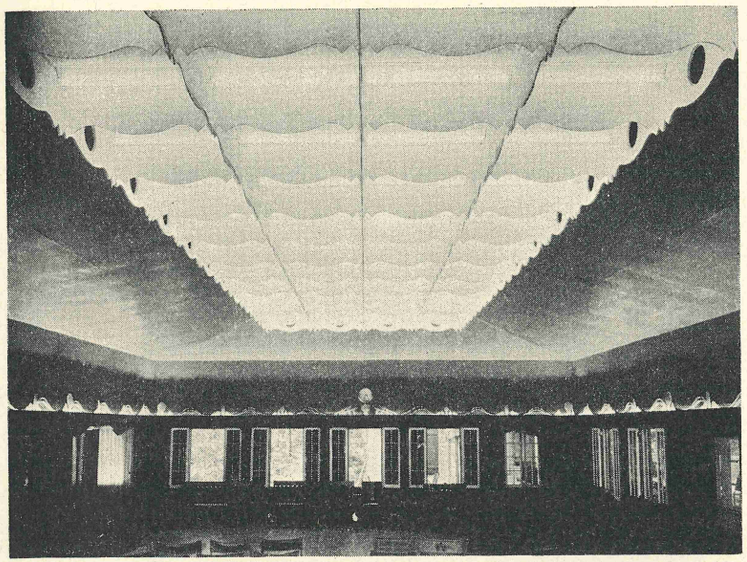


FIG. 207.—A large auditorium lighted by colored fluorescent lamps in decorative coffers. The resultant illumination on the floor is very nearly white.

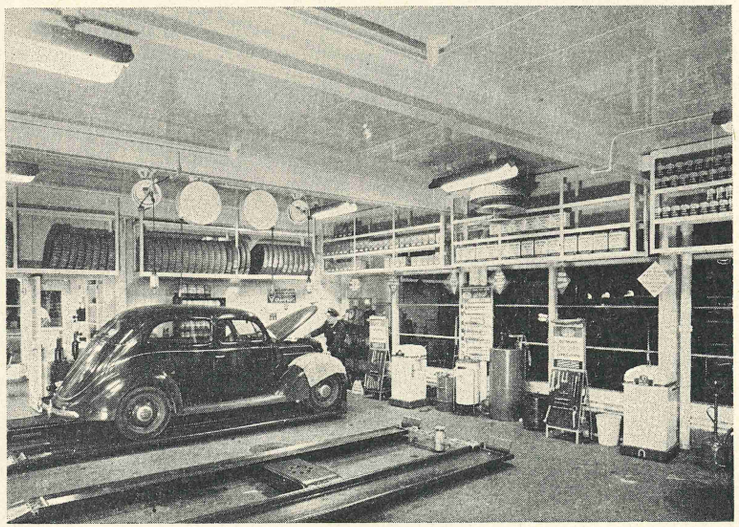


FIG. 208.—Industrial fluorescent luminaires can be used to provide general lighting in the service-station interior, necessary for evening service work and often appreciated during the daylight hours as well.

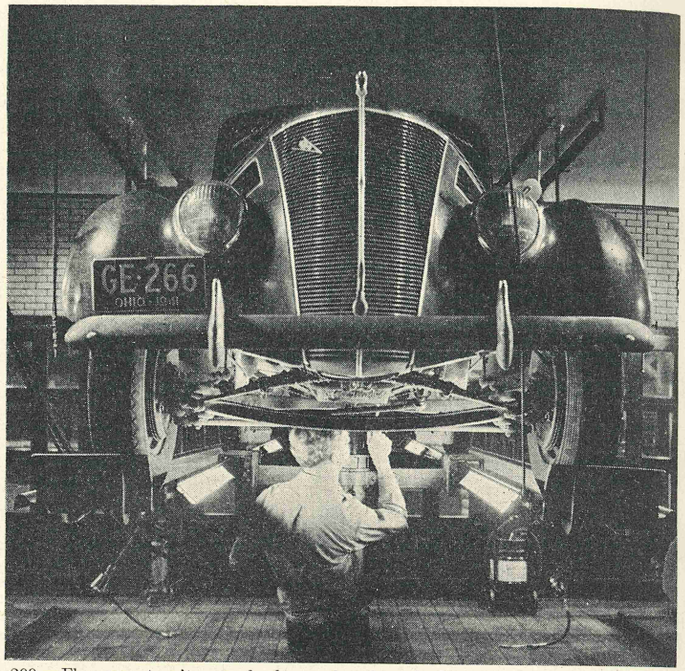


FIG. 209.—Fluorescent units can also be employed on the lift rack to relieve eye strain and avoid mistakes in lubricating hard-to-see fittings.

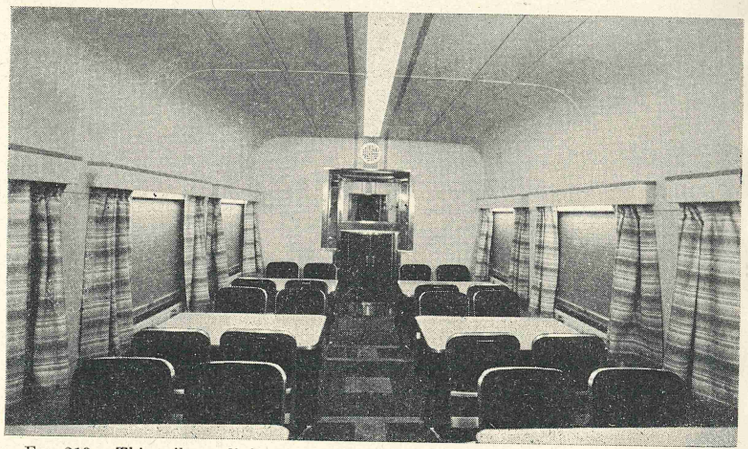


FIG. 210.—This railway dining-car section is lighted by 30-watt white fluorescent lamps recessed in the longitudinal ceiling reflector and in inverted open troughs just above the windows.

CHAPTER X

LIGHTING ECONOMICS

The Low Cost of Good Lighting.—It is an interesting fact that the more a person appreciates the advantages of something, the less concerned he will be about its expense. This is very much true about artificial lighting.

Actually, good modern illumination is quite inexpensive when compared with the many benefits it brings. A few of the advantages of higher footcandle levels were listed in Chap. VII. This "inexpensiveness" holds true regardless of the illuminant—fluorescent, mercury, or incandescent-filament lighting. In a typical store, for example, an average increase of 3 per cent in the volume of sales because of high-quality lighting over the sales volume *with no lighting at all* would justify the cost of the lighting. Since all stores have some lighting already, the percentage of increased volume needed to justify higher quality lighting is more on the order of 1½ per cent. And merchants testify to the ability of improved lighting to increase sales volume, accompanied at the same time by other benefits such as decreased return merchandise and a lower rate of labor turnover because of the more pleasant surroundings. In fact, a combination of even minor influences on the sales operation would easily justify a high-quality lighting installation for modern merchandising efforts.

Analyzing the cost of good lighting vs. the advantages will show that the benefits considerably exceed the cost not only for stores but for any type of interior. Experience will also prove that it is economically sound to use fluorescent lamps on the basis of providing footcandle levels approaching those known to be desirable for the task at hand, rather than applying them in unprogressive installations on a superficial notion of saving money on operating costs, usually at a sacrifice of lighting quality or future satisfaction with the installation.

Just as it is necessary to appreciate the benefits of good modern lighting, so it is necessary to make accurate cost com-

parisons if the analysis is to be complete and correct. For example, although it is true that fluorescent lamps are about two or two and a half times as efficient as the incandescent-filament lamps commonly employed for general lighting, it does not necessarily follow that two and a half times as much light can be secured for the same money with fluorescent lighting. Actually, the cost of the current is only a part of the total cost of the light, and it is the purpose of the chapter to show how the first cost of the installation, depreciation rate, energy cost, lamp efficiency, utilization of the light, and several other items enter the cost-analysis picture. For example, fluorescent luminaires are, generally speaking, more expensive than incandescent fixtures, and the higher owning cost of the fluorescent installation will partly offset the lower current cost.

Frequently, the purely economical analysis discloses that the over-all cost of good lighting over a period of time with either filament or fluorescent lamps is about the same when all the factors are considered. Even if one illuminant or the other has a cost advantage for a given case, the difference will probably be small enough that the customer will make his choice on other than economical considerations.

Making Accurate Cost Comparisons.—The most important reason why every lighting engineer should understand and be able to use a sound method of cost analysis is to compare the costs of various ways of solving a particular lighting task. In almost every case, several designs will be considered before either the lighting engineer or the customer makes his final choice. However, it is often undesirable to overemphasize the cost angle in sales presentations. Stress the advantages of good lighting instead.

Of course, there are many ways in which to figure the cost of a lighting installation. Some consider only lamp replacement and power cost. Others divide the initial cost by the number of years they expect to use the installation and add that so-called "annual owning cost" to the operating cost (lamp replacements plus electrical energy). Obviously, these two methods are both inaccurate, and neither should be employed. The best method involves a consideration of the interest, maintenance, taxes, wiring, insurance, depreciation, utilization, etc. Of the items just mentioned, perhaps the most difficult on which to generalize

is that of depreciation—which will depend on the type of interior, the quality of installation, and, of most importance, the customer's system for estimating equipment life and allowing for depreciation. At any rate, the yearly owning cost will be a sum of the depreciation, interest and taxes, insurance, and maintenance.

Many lighting men think that the initial cost of equipment should be amortized in 6 years, assuming that the lighting art is expanding rapidly today and a change will be desirable at the end of that time. On such an amortization basis, the yearly owning cost will be: depreciation, 16⅔ per cent; interest (at 6 per cent on the declining principal), 3 per cent; taxes, insurance, and maintenance, 5 per cent. The total is 24⅔ per cent, or 25 per cent in round numbers. Some customers, however, feel that such an amortization means writing off the initial equipment cost too rapidly and prefer to use 8 years, in which case the yearly owning cost becomes: depreciation, 12½ per cent; interest (again at 6 per cent on the declining principal), 3 per cent; and taxes, insurance, and maintenance, 5 per cent—a total of 20 per cent. There are still some customers, particularly industrials, who prefer to write off the equipment in a 12-year period, and the yearly owning cost becomes: depreciation 8⅓ per cent; interest, 3 per cent; taxes, insurance, and maintenance, 5 per cent—a total of 16 per cent.

Many lighting engineers use a yearly owning cost of 20 per cent for office, school, and store lighting installations and 16 per cent for industrial jobs. However, these values may vary depending on the case at hand and on the customer's method of determining depreciation allowances.

The Various Factors and Their Relative Influences.—The total annual cost of a lighting system of any type is equal to the sum of the annual fixed charges (or yearly owning cost), the annual lamp cost, and the annual energy cost. If this total annual cost is then divided by the average footcandle level obtained in service, the cost per footcandle year will include all the relevant factors, and the cost analysis will be on a sound and logical basis.

Because fluorescent-lighting equipment is, generally speaking, more expensive initially than filament luminaires of the common variety, the yearly owning cost will often be higher for a fluores-

cent system. Of course, by the same token, fluorescent equipment designed and constructed basically for competitive selling will have a lower initial cost which will reflect favorably in the cost analysis.

In calculating depreciation, the cost of units should be the net cost to the customer. Wiring costs are included in the first cost of new installations and in relighting installations when new wiring is required. Wiring costs will, of course, vary considerably. The actual wiring cost should be used wherever possible. Strictly speaking, the wiring cost should be amortized over a longer period than is allowed for the lighting units, since in most cases the wiring system will outlive the lighting installation.

The net cost of lamps should be used in these computations. If the installation is of appreciable size, it is likely that the customer is getting a discount on the lamps initially installed and on all lamp replacements. Incidentally, with the prices of fluorescent lamps considerably reduced, and with lamp-life ratings increased (because of design and manufacturing improvements and mortality experience), the annual lamp-cost picture of fluorescent vs. filament lamps is considerably different than it was 2 years ago.

Energy costs include demand charges where they exist. Too, the customer must consider the possible influence on his rate structure should different amounts of power be consumed with the new lighting installation. Certainly if the customer plans a fluorescent installation on the basis of reducing energy consumption, it is highly possible that the lower kilowatt-hours may throw him into higher power-rate classification. On the other hand, the customer who uses fluorescent lighting as a means of providing optimum seeing, production, or display conditions may find that the new load is actually greater than the old and a lower rate classification may be possible.

A Typical Comparison Problem.—Table 39 indicates the manner in which cost-analysis problems can be easily set up. The problem was to determine the relative cost of lighting an industrial area 75 by 112 ft. to an illumination level of 50 footcandles in service with (1) a system of 500-watt Glassteel Diffusers,[1] (2) 40-watt two-lamp RLM fluorescent luminaires

[1] This fixture was selected because it produces light of a quality comparable to that of the fluorescent RLM system.

TABLE 39.—LIGHTING COST COMPARISONS FOR PROVISION OF 50 FOOTCANDLES IN SERVICE IN A 75 BY 112 FT. AREA
(No cost included for cleaning or servicing burned-out lamps)

Item	500-watt Glassteel diffusers	40-watt RLM fluorescent, individually located	40-watt RLM fluorescent, continuous row
Lamps per unit	One 500-watt clear	Two 40-watt white	Two 40-watt white
Lamp lumens per unit	10,000	4200	4200
Reflector efficiency	66 %	79 %	79 %
Lamp life, hours	1000	2500	2500
Lamp watts per unit	500	80	80
Ballast loss per unit, watts	.....	17½	17½
Total watts per outlet	500	97½	97½
Illumination Design:			
Room Index	*A*	*A*	*A*
Color walls/ceiling	50/30	50/30	50/30
Coefficient of utilization	.58	.69	.69
Maintenance factor	0.70	0.75	0.75
Number of outlets	104	193	193
Equipment Cost:			
Contractor's cost per unit	$7.63	$15.00	$14.84
List price per lamp	1.10	1.15	1.15
Net price, lamps per unit at 30 % off	0.77	1.61	1.61
Installation Cost:			
Initial lamp cost	$ 80.80	$ 310.73	$ 310.73
Fixture cost	793.52	2895.00	2864.12
Wiring cost	1040.00	965.00	579.00
Fixture and wiring cost	1833.52	3860.00	3443.12
Annual Owning Cost (20 % per year):			
Fixtures (no wiring)	$ 158.70	579.00	572.82
Fixtures and wiring	366.70	772.00	688.62
Annual Operating Cost:			
Annual lamp cost	$ 160.16	248.58	248.58
Energy cost per year at 1¢ per kw.-hr.*	1040.00	376.35	376.35
Total operating cost per year	1200.16	624.93	624.93
Total Annual Cost:			
Cost (less wiring)	$1358.86	1203.93	1197.75
Cost (with wiring)	1566.86	1396.93	1313.55
Cost per footcandle (less wiring)	27.18	24.08	23.96
Cost per footcandle (with wiring)	31.34	27.94	26.27
Cost Comparisons:			
First cost per sq. ft. fixtures only	9.4¢	34.4¢	34.1¢
First cost per sq. ft. fixtures and wiring	21.8¢	46.0¢	41.0¢
Annual operating cost per sq. ft.	14.3¢	7.4¢	7.4¢
Total annual cost per sq. ft. (with wiring)	18.7¢	16.6¢	15.6¢
Cleaning and Servicing:			
Number of reflectors	104	193	193
Reflector area per unit, sq. ft.	8.2	8.5	8.5
Total reflector area, sq. ft.	850	1640	1640
Lamps replaced per year	208	309	309

* Burning hours 2000 a year.

individually located, and (3) continuous rows of 40-watt two-lamp RLM fluorescent luminaires. The tabulation is self-explanatory. The analysis is complete except that no cost is included for cleaning or servicing burned-out lamps.

Note that of the two 40-watt fluorescent systems, the cost is less for continuous rows than for similar equipment on a conventional-unit arrangement. The 500-watt Glassteel Diffuser cost is 3 cents per sq. ft. more than the continuous-row fluorescent system. The advantage of the continuous-row system over the individual unit system lies in the decreased wiring costs.

It will be interesting to compare the total annual cost per square foot given in the tabulation of Table 39 with those of several other types of systems with which this same area could be lighted to 50 footcandles.

Type of System	Total Annual Cost per Square Foot, Cents
100-watt RLM fluorescent conventional unit system*	16.3
100-watt continuous row RLM*	15.3
400-watt H-1 mercury lamps in Glassteel Diffusers	15.7
500-watt RLM domes	16.5

* With vents.

One cent per kilowatt-hour was used in the above tabulation and in Table 39, but the effect of other energy costs will be seen in Fig. 211. Note that the 40-watt continuous-row RLM installation is less expensive than the 500-watt Glassteel filament installation at all energy rates over 0.6 cents per kw.-hr., for that is the point at which their cost curves cross.

Of course, costs can be determined on the basis of so many dollars per footcandle year for the entire installation or for a footcandle year over a smaller area, say 100 sq. ft. Still other methods will be apparent—since in Table 39 equal footcandle levels were provided by three different types of systems, the footcandle level maintained in service is automatically included in the cost calculations and the result need simply be in "cents per square foot," or its equivalent. Obviously, in working with customers, it would frequently be advisable to simplify the cost-analysis method to conform to his particular system. In any case, however, use good judgment in preparing and presenting cost computations for too frequently they indicate an accuracy

unjustified by the available data. If the procedure is mastered, it will be simple to apply this cost-comparison method to office lighting, store lighting, school lighting, or any other particular illumination field. By working a few problems, the effects of annual burning hours, energy rates, initial cost, depreciation rates, etc., will become apparent.

The Cost of High-voltage Fluorescent-tubing vs. Standard Fluorescent-lamp Systems.—The question has often been asked as to the relative cost of doing a given lighting job calling

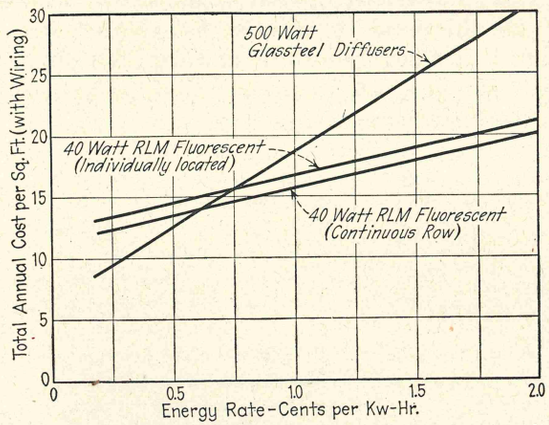


FIG. 211.—Comparative costs (in cents per square foot) for providing 50 footcandles in service in a factory area 75 × 112 feet operating 2000 hr. annually. Calculations include wiring but not cost of cleaning or servicing burned-out lamps.

for specified maintained footcandle levels with high-voltage fluorescent tubing vs. standard fluorescent lamps. By following the accepted cost-analysis procedure outlined above, it can be shown just what particular system offers the customer the most for his lighting dollar.

"Keeping Sight of the Wood."—The old expression "Ye cannot see the wood for the trees" is an appropriate one in connection with comparative cost figures of lighting installations. It cannot be too strongly emphasized that the benefits of good modern lighting far outweigh its cost—that light's humanitarian value is alone enough to justify 50 footcandles *or more* of comfortable illumination wherever the seeing task is critical or prolonged.

Lighting-cost comparisons should not be over emphasized because (1) such analyses do not consider the quality of the lighting (which is so important in securing comfortable seeing conditions) and (2) the cost of cleaning and servicing is usually not included. In addition, wiring costs are often difficult to obtain.

It is significant to recall that the average cost of light is now about one-thirtieth of what it was in 1890—and it is still going down. This is for a given amount of light, based on average wattage sizes and the average cost of lamps and electric energy. Coupled with this steady progress is the amazing increase in the use of light. It seems safe to predict that the public will use increasingly more as costs go down and the advantages of abundant light become more generally known.

APPENDIX

DEFINITIONS

ambient temperature: The temperature of the surrounding air.

anode: The positive terminal of an electric discharge to which the electrons supplied by the cathode flow. In most instances involving alternating-current operation, electrodes act alternately as cathode and anode.

apparent candlepower: The candlepower of a point light source which would produce the same illumination at the specified distance. The term is frequently seen in connection with candlepower-distribution data of extended light sources such as fluorescent luminaires.

argon gas: A colorless and odorless gaseous element found in scant quantities in ordinary air. Argon is used as a starting medium in fluorescent lamps because it ionizes, or conducts electricity, at relatively low voltage potentials.

auxiliary: Fluorescent auxiliary equipments are those devices necessary for the proper starting and operation of the lamp. Early fluorescent "auxiliaries" consisted of a choke coil and starting switch contained together in a single case.

ballast: A device used to limit the flow of current in an electric-discharge lamp. In most instances, ballasts take the form of reactors, or "choke coils," although in some cases resistance ballasts are employed.

brightness: The degree of brilliancy of any part of a surface or medium, when viewed from a designated direction. It is measured by the ratio of the candlepower emitted in that direction to the apparent area as seen from that direction. In all ordinary cases, brightness is independent of the distance of observation.

bulb-wall temperature: The temperature of the glass tube of the fluorescent lamp.

candlepower: The unit of luminous intensity in any given direction.

candles per square inch: A unit of brightness equal to 1 candlepower emitted or reflected per square inch of surface. One candle per square inch is equal to 452 footlamberts.

cathode: The negative terminal of the electric discharge, *i.e.*, the electrode that supplies the electrons necessary to sustain the arc.

Cooper-Hewitt lamp: A low-pressure mercury-vapor lamp named for its inventor, Peter Cooper Hewitt, and first exhibited in 1901.

current density: The lamp current per unit of cross-sectional area of the discharge path.

degrees Kelvin: An absolute temperature scale equal to the temperature in degrees centigrade plus 273.

diffuse reflection: Reflection in which the light is reflected in all directions.

efficiency of light production: The lumen output per watt of power input. For light sources such as the fluorescent lamp, where auxiliary equipment is required, the over-all efficiency is based on the total wattage input (lamp watts plus auxiliary watts). The efficiency of luminaires, reflectors, and other accessories is given as the percentage of the total light output of the lamp (bare-lamp lumens) actually delivered by the luminaire, reflector, or accessory.

electric-discharge lamp: A lamp in which light is produced by the passage of electricity through a metallic vapor or a gas enclosed in a tube or bulb.

electrode: In this manual, the terminal of an electric discharge.

electron: The most elementary charge of negative electricity. Electrons help comprise the miniature solar system of all atoms.

electron-emissive material: In this manual, a substance that emits electrons freely when heated.

filament lamp: A light source consisting of a glass bulb containing a filament electrically maintained at incandescence.

fluorescence: The production of light by the transformation of invisible ultraviolet energy into visible light. Substances having this property are called fluorescent materials, and they emit light only while the exciting radiation is present. Phosphorescence, on the other hand, is the property of "shining in the dark" after exposure to light, as do radium dials on clocks, etc. The cobbler of Bologna (mentioned at the beginning of the manual) actually witnessed phosphorescence.

footcandle: The unit of illumination and the measure of density of the light falling on any surface. It is defined as the illumination on a surface one foot square received from a source one foot away which emits one candlepower in the direction of the surface. A footcandle is produced by one lumen received on one square foot of area—10 footcandles is equal to 10 lumens per square foot. When light from a point source falls perpendicularly on a plane, the illumination in footcandles on the plane is equal to the candlepower emitted by the source in that direction divided by the square of the distance in feet.

footlambert: A unit of brightness, equal to one lumen per square foot reflected or emitted by a perfectly diffusing surface. Since most surfaces or mediums are not perfectly diffusing, the brightness varies with the point of view. The average brightness of any reflecting surface in footlamberts is, however, the product of the average illumination in footcandles multiplied by the reflection factor of the surface.

glare: Light "out of place" which causes discomfort or interferes with seeing.

infrared energy: The domain of radiant energy having wavelengths greater than light and less than radio waves.

light: Radiant energy evaluated according to its capacity to produce visual sensation. The average eye is tuned to wavelengths between 3800 and 7200 Å., and radiant energy within this wavelength band is evaluated as light.

louvers: Shields placed in the path of light to redirect or to eliminate an undesired part.

lumen: The unit of luminous flux (the time rate of flow of light) equal to the light through a unit solid angle (steradian) from a uniform point source of one candle. The lumen can express the total output of any light source, the output of a point source in any solid angle, the light received upon any area, light absorbed, reflected, or transmitted. The lumens required to illuminate a surface equal the average footcandle level times the square feet of area.

lumens per watt: The commonly used measure of luminous efficiency, *i.e.*, light output divided by wattage input.

luminescence: The production of light by a change in the nature of the luminous material, as distinguished from light produced directly by high temperature.

luminaire: A complete lighting equipment (fixture) including the light source, reflecting, diffusing, or refracting parts, housing, and support.

parabolic reflector: A reflector that has its reflecting surface in the form of a paraboloid or whose cross section is a parabola.

phosphors: The fluorescent and phosphorescent chemicals with which the inside surface of fluorescent lamps are coated.

power factor: In an alternating-current circuit, the power factor is the ratio determined by dividing the watts by the product of voltage and current. A power factor of 50 per cent, for example, means that only one-half of the current being carried by the power lines is doing useful work. In vector diagrams of alternating-current relationships, the power factor appears as a phase-displacement angle between voltage and current. The cosine of this displacement angle is equal to the power factor. Leading and lagging power factors are illustrated in Fig. 22.

radiant energy: Energy traveling in the form of electromagnetic waves.

reflection factor: The ratio of the light reflected by a designated surface or body to the incident light.

specular (or regular) reflection: Reflection in which the angle of reflection is equal to the angle of incidence (see Fig. 99), *i.e.*, there is no scattering of the light by the reflecting surface.

transmission factor: The ratio of the light transmitted by a given medium to the light incident upon it. Transmission may be regular (transparent materials) or diffuse (translucent materials).

ultraviolet energy: Invisible radiant energy of a wavelength somewhat shorter than that of visible light.

visible spectrum: That portion of the electromagnetic spectrum which the eyes appraise as light. It is usually considered the region between 3800 and 7200 Å.

wavelength: The length of the wave of a light ray, usually measured in Angstrom units.

CALCULATING LINE CURRENTS WHERE BALLASTS OF DIFFERENT POWER FACTOR ARE CONNECTED IN PARALLEL

To determine mathematically the total line current that results when two or more ballasts of different power factors are connected

in parallel, it is necessary to resort to the somewhat complicated vector theory of alternating-current circuits. This theory states that whenever the current either leads or lags the voltage (*i.e.*, when the power factor is something other than 100 per cent or unity) part of that current is evidenced in producing useful power, or watts, whereas another portion, at right angles to the useful component, produces no power. This is shown in Fig. 212, the total current read by the ammeter being however the *vector sum* of the useful and useless components instead of the arithmetical sum. For example, a current of 1 ampere at 60 per cent power factor would have a useful component of 0.6 ampere and a useless component of 0.8 ampere. The vector sum is

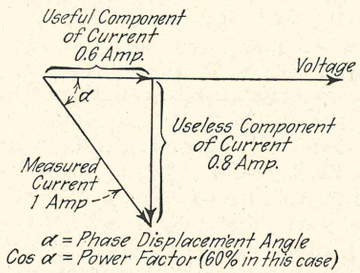


FIG. 212.—Vector diagram of a 1-amp. 60 per cent power-factor circuit.

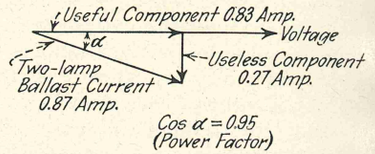


FIG. 213.—Vector diagram of the current relationships of the 40-watt two-lamp ballast used in the text example.

equal to the square root of the sum of the squares of the two components, *i.e.*,

$$\sqrt{(0.6)^2 + (0.8)^2} = 1 \text{ ampere}$$

If ballasts of two different power factors are connected in parallel, the total line current is the vector sum of the two separate currents which are, in turn, both vector expressions themselves. Consider the example given on page 80. The fixture contained two 40-watt lamps operated from a two-lamp ballast consuming 17.5 watts and having an over-all power factor of around 0.95 and one 40-watt lamp operated from a single-lamp uncorrected power factor ballast having a watts loss of 12 watts and an over-all power factor of about 0.60. The line current drawn by the two-lamp ballast will be approximately

$$\frac{80 + 17.5}{(118)(0.95)} = 0.87 \text{ ampere (Fig. 213)}$$

Likewise, the line current drawn by the uncorrected power factor ballast will be approximately

$$\frac{40 + 12}{(118)(0.60)} = 0.735 \text{ ampere (Fig. 214)}$$

These line-current values are those which an ammeter would read if connected between the line and the ballast. The total current consumed by the entire fixture will be equal to the vectorial sum of these two line currents (Fig. 215). This can be shown graphically or mathematically. By using the latter method the total useful power component is equal to the sum of

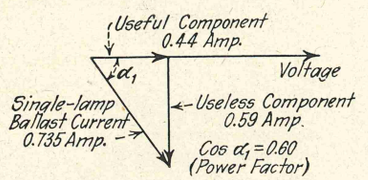


FIG. 214.—The current relationships for the uncorrected power-factor ballast used in the example.

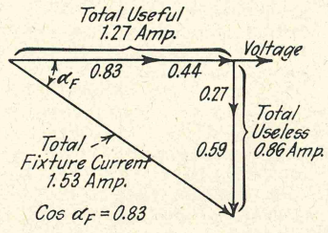


FIG. 215.—The total line current of the 3-lamp fixture—the vector sum of the two ballast currents.

the components of the two ballast currents, *i.e.*, 0.83 + 0.44, or 1.27. The total useless component is, likewise, 0.27 + 0.59, or 0.86. The total fixture current, as read by an ammeter, will be

$$\sqrt{(1.27)^2 + (0.86)^2} = 1.53 \text{ amperes}$$

This method can be applied to any number of lamps and any number of different power factors by determining the total line current at each different power factor and adding these currents vectorially.

The resultant over-all power factor can also be calculated by taking the ratio of the total useful current to the total over-all current, in this case,

$$\frac{1.27}{1.53} = 83 \text{ per cent}$$

the same power factor determined by a different equation on page 81.

RECOMMENDED LEVELS OF ILLUMINATION[1]

FOR INDUSTRIAL INTERIORS

Use	Foot-candles modern practice	Grade* of illumination
Assembly:		
Medium	20	C
Medium fine	50	B
Fine	100	A
Extra fine	200	AA
Automobile manufacturing:		
Assembly line	100	A
Frame assembly	20	C
Body manufacturing—		
Parts	20	C
Assembly	20	C
Finishing and inspecting	200	AA
Bakeries	20	C
Bookbinding:		
Folding, assembling, pasting, etc	10	D
Cutting, punching, and stitching	20	C
Embossing	20	C
Breweries:		
Brewhouse	5	E
Boiling, keg washing, and filling	10	D
Bottling	20	C
Candymaking:		
Box department	20	C
Chocolate department:		
Husking, winnowing, fat extraction, crushing, and refining, feeding	10	D
Bean cleaning and sorting, dipping, packing, wrapping	20	C
Milling	50	B
Creammaking:		
Mixing, cooking, and molding	20	C
Gum drops and jellied forms	20	C
Hand decorating	50	B
Hard candy:		
Mixing, cooking, and molding	20	C
Die cutting and sorting	50	B
Kiss making and wrapping	50	B
Canning and preserving	20	C
Chemical works:		
Hand furnaces, boiling tanks, stationary driers, stationary and gravity crystallizers	5	E
Mechanical furnaces, generators and stills, mechanical driers, evaporators, filtration, mechanical crystallizers, bleaching	10	D
Tanks for cooking, extractors, percolators, nitrators, electrolytic cells	20	C
Clay products and cements:		
Grinding, filter presses, kiln rooms	5	E
Molding, pressing, cleaning, and trimming	10	D
Color, glazing, and enameling	20	C
Cleaning and pressing industry:		
Checking and sorting	20	C
Dry and wet cleaning and steaming	10	D
Inspection and spotting	200	AA
Pressing:		
Machine	20	C
Hand	50	B
Receiving and shipping	10	D
Repair and alteration	200	AA
Cloth products:		
Cutting, inspecting, sewing:		
Light goods	30	C+
Medium goods	100	A
Dark goods	200	AA

[1] Compiled by Walter Sturrock in collaboration with the technical staff of the Nela Park Engineering Department, General Electric Company and reprinted from *Magazine of Light*, No. 6, 1941.

* See Fig. 126 and notes accompanying it.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)

FOR INDUSTRIAL INTERIORS

Use	Foot-candles modern practice	Grade* of illumination
Cloth products.—(*Cont.*)		
Pressing, cloth treating (oilcloth, etc.):		
Light goods	20	C
Medium goods	50	B
Dark goods	100	A
Coal tipples and cleaning plants:		
Breaking, screening, and cleaning	10	D
Picking	200	AA
Construction—indoor General	10	D
Dairy products	20	C
Elevators—freight and passenger	10	D
Engraving	200	AA
Forge shops and welding	10	D
Foundries:		
Charging floor, tumbling, cleaning, pouring, and shaking out	5	E
Rough molding and coremaking	10	D
Fine molding and coremaking	20	C
Garages—automobile:		
Storage	10	D
Repair department and washing	50	B
Glassworks:		
Mix and furnace rooms, pressing, and Lehr, glass-blowing machines	10	D
Grinding, cutting glass to size, silvering	30	C+
Fine grinding, polishing, beveling, etching, and decorating	50	B
Inspection	100	A
Glove manufacturing:		
Pressing, knitting, sorting:		
Light goods	20	C
Medium goods	50	B
Dark goods	100	A
Cutting, stitching, trimming, and inspecting:		
Light goods	30	C+
Medium goods	100	A
Dark goods	200	AA
Hangars—airplane	50	B
Hat manufacturing:		
Dyeing, stiffening, braiding, cleaning, and refining:		
Light	20	C
Medium	50	B
Dark	100	A
Forming, sizing, pouncing, flanging, finishing, and ironing:		
Light	20	C
Medium	50	B
Dark	100	A
Sewing:		
Light	30	C+
Medium	100	A
Dark	200	AA
Ice making—engine and compressor room	10	D
Inspection:		
Medium	20	C
Medium fine	50	B
Fine	100	A
Extra fine	200	AA
Jewelry and watch manufacturing	200	AA
Laundries	30	C+
Leather manufacturing:		
Vats	5	E
Cleaning, tanning, and stretching	10	D
Cutting, fleshing, and stuffing	20	C
Finishing and scarfing	30	C+

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* See Fig. 126 and notes accompanying it.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)

FOR INDUSTRIAL INTERIORS

Use	Foot-candles modern practice	Grade* of illumination
Leather working:		
Pressing, winding, and glazing:		
Light	20	C
Medium	50	B
Dark	100	A
Grading, matching, cutting, scarfing, sewing:		
Light	30	C+
Medium	100	A
Dark	200	AA
Locker rooms	10	D
Machine shops:		
Rough bench and machine work	20	C
Medium bench and machine work, ordinary automatic machines, rough grinding, medium buffing, and polishing	30	C+
Fine bench and machine work, fine automatic machines, medium grinding, fine buffing and polishing	100	A
Extra fine bench and machine work, grinding:		
Fine work	200	AA
Meat packing:		
Slaughtering	10	D
Cleaning, cutting, cooking, grinding, canning, packing	20	C
Milling—grain foods:		
Cleaning, grinding, and rolling	10	D
Baking or roasting	20	C
Flour grading	30	C+
Offices:		
Bookkeeping, typing, and accounting	50	B
Business machines—calculators, key punch, bookkeeping—local illumination	100	A
Conference room:		
General meetings	30	C+
Office activities—*see* Desk work		
Corridors and stairways	5	E
Desk work:		
Intermittent reading and writing	30	C+
Prolonged close work, computing, studying, designing, reading blueprints and plans	50	B
Drafting:		
Prolonged close work—art drafting and designing in detail	50	B
Filing and index references	30	C+
Lobby	20	C
Mail sorting	30	C+
Reception rooms	20	C
Stenographic work:		
Prolonged reading shorthand notes	50	B
Vault	20	C
Packing and boxing	10	D
Paint mixing	10	D
Paint shops:		
Dipping, spraying, firing, rubbing, ordinary hand painting and finishing	20	C
Fine hand painting and finishing	50	B
Extra fine hand painting and finishing (automobile bodies, piano cases, etc.)	100	A
Paper-box manufacturing:		
Light	10	D
Dark	50	B
Storage	5	E

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* See Fig. 126 and notes accompanying it.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)

FOR INDUSTRIAL INTERIORS

Use	Foot-candles modern practice	Grade* of illumination
Paper manufacturing:		
Beaters, grinding, calendering	10	D
Finishing, cutting, trimming	20	C
Plating	10	D
Polishing and burnishing	20	C
Power plants, engine room, boilers:		
Boilers, coal and ash handling, storage battery rooms	5	E
Auxiliary equipment, oil switches, transformers, engines, generators, blowers, compressors	20	C
Control room:		
Switchboards and meters	30	C+
Printing industries:		
Type foundries:		
Matrix making, dressing type	100	A
Font assembly—sorting	50	B
Hand casting	30	C+
Machine casting	20	C
Photography:		
Dry plate and film	2000	AAAA
Wet plate	3000	AAAA
Printing on metal	2000	AAAA
Electrotyping:		
Molding, routing, finishing, leveling molds	100	A
Trimming	50	B
Blocking, tinning	30	C+
Electroplating, washing, backing	20	C
Photoengraving:		
Etching, staging	20	C
Blocking	30	C+
Proofing	50	B
Tint laying, routing, finishing	100	A
Printing plants:		
Presses	30	C+
Imposing stones	.....	A‡
Proofreading	100	A
Protective industrial	0.2	G
Receiving and shipping	10	D
Rubber goods—mechanical:		
Stock preparation:		
Plasticating, milling, and branbury	20	C
Calendering	30	C+
Fabric preparation—stock cutting and hose looms	30	C+
Extruded products	30	C+
Molded products and curing	50	B
Inspection	100	A
Boxing	20	C
Warehouse	5	E
Rubber-tire and tube manufacturing:		
Stock preparation:		
Plasticating, milling, and branbury	20	C
Calendering	30	C+
Fabric preparation—stock cutting and bead building	30	C+
Tube and tread tubing machines	20	C
Tire building:		
Solid tires	20	C
Pneumatic tires	50	B
Curing department:		
Tube and casing	50	B
Final inspection:		
Tube	50	B
Casing	100	A
Wrapping	20	C
Warehouse	5	E

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* See Fig. 126 and notes accompanying it.

‡ Large-area light sources of low surface brightness and good diffusion are necessary for the inspection of shiny or polished work surfaces or parts.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)

FOR INDUSTRIAL INTERIORS

Use	Foot-candles modern practice	Grade* of illumination
Sheet-metal works:		
Miscellaneous machines, medium benchwork, punches, presses, shears, stamps, welders, spinning	20	C
Tin-plate and similar inspection	.....	B‡
Shoe manufacturing (leather):		
Cutting and stitching:		
Cutting tables	20	C
Marking, buttonholing, skiving, sorting, vamping, and counting:		
Light materials	20	C
Dark materials	100	A
Stitching:		
Light materials	30	C+
Dark materials	200	AA
Making and finishing:		
Stitchers, nailers, sole layers, welt beaters and scarfers, trimmers, welters, lasters, edge setters, sluggers, randers, wheelers, treers, cleaning, spraying, buffing, polishing, embossing:		
Light materials	20	C
Dark materials	100	A
Storage, packing, and shipping	10	D
Shoe manufacturing (rubber)		
Washing, coating, mill-run compounding	10	D
Varnishing, vulcanizing, calendering, upper and sole cutting	30	C+
Sole rolling, lining, making and finishing processes	50	B
Silk and rayon manufacturing:		
Soaking, fugitive tinting, and conditioning or setting of twist	10	D
Winding, twisting, rewinding, and coning, quilling, slashing	30	C+
Warping (silk or cotton system) on creel, on running ends, on reel, on beams, on warp at beaming	50	B
Drawing in:		
On heddles and on reed	100	A
Weaving:		
On heddles and reeds	10	D
On warp back of harness	20	C
On woven cloth	30	C+
Soap manufacturing:		
Kettle houses, cutting, soap chip, and powder	10	D
Stamping, wrapping, and packing, filling, and packing soap powder	20	C
Stairways, corridors, and passageways	5	E
Steel and iron manufacturing:		
Billet, blooming, sheet, bar, skelp, and slabbing mills	10	D
Boiler room, powerhouse, foundry and furnace rooms	10	D
Hot sheet and hot strip mills	10	D

[1] Compiled by Walter Sturrock in collaboration with the technical staff of the Nela Park Engineering Department, General Electric Company and reprinted from *Magazine of Light*, No. 6, 1941.

* See Fig. 126 and notes accompanying it.

‡ Large-area light sources of low surface brightness and good diffusion are necessary for the inspection of shiny or polished work surfaces or parts.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)

FOR INDUSTRIAL INTERIORS

Use	Foot-candles modern practice	Grade* of illumination
Steel and iron manufacturing (*Cont.*)		
Cold strip, pipe, rail, rod, tube, universal plate and wire drawing	10†	D
Merchant and sheared-plate mills	20†	C
Tin-plate mills:		
Hot strip rolling and tinning machine department	10	D
Cold strip rolling	20	C
Inspection:		
Black plate, bloom, and billet chipping	30	C+
Tin plate and other bright surfaces	.....	B‡
Machine shops and maintenance department, repair shops:		
Rough bench and machine work	20	C
Medium bench and machine work	30	C+
Fine work—buffing, polishing, etc	100	A
Extra fine work	200	AA
Blacksmith shop	10	D
Laboratories (chemical and physical), carpenter and pattern shop	30	C+
Storage	2	F
Stone crushing and screening:		
Belt conveyor tubes, main line shafting spaces, chute rooms, inside of bins	5	E
Primary breaker room, auxiliary breakers:		
Under bins	5	E
Screens	10	D
Storage battery manufacturing:		
Molding of grids	20	C
Store and stock rooms:		
Rough, bulky material	5	E
Medium or fine material requiring care	10	D
Structural steel fabrication	10	D
Sugar grading	30	C+
Testing:		
Rough	20	C
Fine	30	C+
Extra fine instruments, scales, etc	100	A
Textile mills (cotton):		
Opening, mixing, picking, carding, and drawing	10	D
Slubbing, roving, spinning, spooling	20	C
Grading	100	A
Warping on comb	30	C+
Beaming and slashing on comb:		
Gray goods	20	C
Denims	100	A
Inspection:		
Gray goods (hand turning)	50	B
Denims (rapidly moving)	200	AA
Automatic tying in, weaving	50	B
Drawing-in by hand	100	A
Tobacco products:		
Drying, stripping, general	10	D
Grading and sorting	100	A
Toilets and washrooms	10	D

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* See Fig. 126 and notes accompanying it.

† In these areas many of the machines require one or more supplementary lighting units mounted on them in order to direct light effectively toward the working points.

‡ Large-area light sources of low surface brightness and good diffusion are necessary for the inspection of shiny or polished work surfaces or parts.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)

For Industrial Interiors

Use	Foot-candles modern practice	Grade* of illumination
Upholstering—automobile, coach, furniture	20	C
Warehouse	5	E
Woodworking:		
Rough sawing and bench-work	10	D
Sizing, planing, rough sanding, medium machine and benchwork, gluing, veneering, cooperage	20	C
Fine bench and machine work, fine sanding and finishing	50	B
Woolen:		
Carding, picking, washing, combing, twisting, dyeing	10	D
Drawing in, warping:		
Light goods	20	C
Medium goods	50	B
Dark goods	100	A
Weaving:		
Light goods	20	C
Medium goods	50	B
Dark goods	100	A
Knitting machines	20	C

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*See Fig. 126 and notes accompanying it.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)

For Offices, Drafting Rooms, Schools, and Public Buildings

Use	Foot-candles modern practice	Grade* of illumination
Armories:		
Drill	10	D
Exhibitions	20	C
Art galleries:		
General	10	D
On paintings—local illumination	50	B
Auditoriums	10	D
Banks:		
Lobby	20	C
Cages and offices	50	B
Barber shops	50	B
Churches:		
Auditoriums	5	E
Sunday-school rooms	20	C
Pulpit or rostrum—local illumination	20	C
Art glass windows:		
Light color	20	C
Medium color	100	A
Dark color	200	AA
Club and lodge rooms:		
Lounge and reading rooms	20	C
Auditoriums	10	D
Courtrooms	20	C
Drafting rooms:		
Prolonged close work, art drafting and designing in detail	50	B
Fire-engine houses	10	D
Garages—automobile:		
Storage	10	D
Repair and washing departments—local illumination	50	B
Hangars—airplane	50	B
Hospitals:		
Corridors	5	E
Laboratories	30	C+
Lobby and reception room	20	C
Operating room:		
General	50	B
Operating table:		
Major operations	1000	AAAA
Minor operations	200	AA
Private rooms and wards—local illumination	30	C+
Hotels:		
Lobby	20	C
Dining room	5	E
Kitchen	20	C
Guest rooms—local illumination	30	C+
Corridors	5	E
Writing rooms—local illumination	30	C+
Library:		
Reading room	30	C+
Stack room	10	D
Museums:		
General	10	D
Special displays—local illumination	50	B
Office buildings:		
Bookkeeping, typing, and accounting	50	B
Business machines:		
Calculators, key punch, bookkeeping—local illumination	100	A
Conference room:		
General meetings	30	C+
Office activities—*see* Desk work		
Corridors and stairways	5	E
Desk work:		
Intermittent reading and writing	30	C+
Prolonged close work, computing, studying, designing, reading blueprints and plans	50	B
Filing and index references	30	C+
Lobby	20	C
Mail sorting	30	C+
Reception rooms	20	C
Stenographic work:		
Prolonged reading shorthand notes	50	B
Vault	10	D
Post office:		
Lobby	20	C
Sorting, mailing, etc.	30	C+
Storage	10	D

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*See Fig. 126 and notes accompanying it.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)

For Offices, Drafting Rooms, Schools, and Public Buildings

Use	Foot-candles modern practice	Grade* of illumination
Post office (*Cont.*)		
File room	30	C+
Corridors and stairways	5	E
Professional offices:		
Waiting rooms	20	C
Consultation rooms	30	C+
Examination rooms—local illumination	100	A
Dental chairs—local illumination	200	AA
Schools:		
Auditoriums	10	D
Class and study rooms—desks and blackboards	30	C+
Corridors and stairways	5	E
Drawing room	50	B
Gymnasium	20	C
Laboratories:		
General	30	C+
Close work—local illumination	50	B
Lecture rooms:		
General	20	C
Special exhibits and demonstrations—local illumination	50	B
Manual training:		
General	30	C+
Close work—local illumination	100	A
Sewing room—local illumination	100	A
Sight-saving classes	50	B
Service space:		
Corridors	5	E
Elevators—freight and passenger	10	D
Halls and stairways	5	E
Storage	10	D
Toilets and washrooms	10	D
Transportation:		
Cars:		
Baggage, day coach, dining, Pullman	20	C
Mail:		
Bag racks and letter cases	30	C+
Storage	5	E
Street railway, trolley, bus, subway	30	C+
Motor bus	30	C+
Depots:		
Waiting rooms	20	C
Ticket offices:		
General	20	C
Ticket rack and counters—local illumination	50	B
Rest rooms, smoking rooms	20	C
Baggage checking offices	20	C
Storage	5	E
Concourse	5	E
Platforms	5	E
Toilets and washrooms	10	D

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* See Fig. 126 and notes accompanying it.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)

For Merchandising, Display, and Entertainment

Use	Foot-candles modern practice	Grade* of illumination
Store interiors:		
Circulating areas	20	C
General merchandising areas	50	B
Showcases, wall cases, and open counter displays	100	A
Feature displays	200	AA
Stock rooms	10	D
Show windows:		
Small cities and towns:		
General	50	B
Feature displays	100	A
Large cities—secondary business areas:		
General	100	A
Feature displays	200	AA
Large cities—main business areas—general	200	AA
Feature displays	500	AAA
Minimizing daylight reflections	1000	AAAA
Automobiles:		
Showrooms	50	B
Used-car lots:		
Front row of cars	50	B
Remainder of area	10	D
Barber shops and beauty parlors	50	B
Building exteriors and monuments—floodlighted:		
Bright surroundings:		
Light surfaces	10	D
Dark surfaces	20	C
Dark surroundings:		
Light surfaces	5	E
Dark surfaces	10	D
Bulletin and poster boards:		
Bright surroundings:		
Light surfaces	50	B
Dark surfaces	100	A
Dark surroundings:		
Light surfaces	20	C
Dark surfaces	50	B
Dance halls	5	E
Flags—floodlighted	30	C+
Gasoline service stations:		
Yard	10	D
Pump island and sales-room	30	C+
Lube room:		
General	20	C
Work areas, lube repair, and washing	50	B
Lavatories	10	D
Monuments—*see* Building exterior		
Night clubs and bars	5	E
Restaurants, lunch rooms, cafeterias:		
Dining area	10	D
Food displays	50	B
Smokestacks—with advertising messages	20	C
Theaters and motion-picture houses:		
During intermission	5	E
During picture	0.1	G
Foyer	10	D
Lobby	20	C
Water tanks—with advertising messages	20	C

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* See Fig. 126 and notes accompanying it.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)
FOR RECREATIONAL AREAS

Use	Foot-candles modern practice	Grade* of illumination
Badminton:†		
Back court	10	D
Near net	20	C
Baseball:†		
Seats:		
During game	2	F
Before and after game	5	E
Infield:		
Minor league	50	B
Major league	100	A
Outfield:		
Minor league	30	C+
Major league	100	A
Baseball†—softball (indoor and outdoor)	30	C+
Basketball:		
Recreational	20	C
Exhibition games	30	C+
Bathing beaches	1	G
Billiards:		
General	10	D
On tables	50	B
Bowling:		
General	10	D
On pins	50	B
On the green	10	D
Boxing:		
Seats:		
During bout	2	F
Before and after bout	5	E
Ring:		
Amateur	100	A
Professional	200	AA
Championship	500	AAA
Clock golf	10	D
Croquet	5	E
Football:†		
Practice	10	D
Games	20	C
Gymnasium:		
Locker and shower rooms	10	D
Exercising room—fencing, boxing, wrestling, basketball, volleyball, and softball:		
General exercising	20	C
Exhibition games and matches	30	C+
Handball	30	C+
Horseshoe pitching	10	D
Ice hockey:		
Outdoor	10	D
Indoor	30	C+
Motordromes:		
Seats	2	F
Track	20	C
Playgrounds	5	E
Polo	5	E
Racquet	30	C+
Roque	5	E
Skating rink (indoor)	10	D
Skating (outdoor)	5	E
Squash	30	C+
Swimming pools	10	D
Table tennis—ping-pong	50	B
Target shooting (on target)	50	B
Tennis:		
Recreational	20	C
Exhibition matches	30	C+
Toboggan slides	2	F
Trap shooting (on bird at trap)	100	A
Volleyball:		
Recreational	20	C
Exhibition matches	30	C+

[1] Compiled by Walter Sturrock in collaboration with the technical staff of the Nela Park Engineering Department, General Electric Company and reprinted from *Magazine of Light*, No. 6, 1941.

* See Fig. 126 and notes accompanying it.

† For these games, it is most important to have the proper location and adjustment of lighting units to give adequate visibility for players and spectators. The footcandle values are given primarily to form a basis for calculating the wattage requirement for the field.

RECOMMENDED LEVELS OF ILLUMINATION.[1]—(*Continued*)
FOR BUILDING CONSTRUCTION, STORAGE YARDS, AND OTHER OUTDOOR AREAS

Use	Foot-candles modern practice	Grade* of illumination
Automobile parking spaces	1	G
Building:		
Construction	10	D
Excavation work	5	E
Coalyards—protective	0.2	G
Dredging	2	F
Drill fields	5	E
Loading docks	5	E
Lumber yards	1	G
Piers:		
Freight	5	E
Passenger	5	E
Prison yards	5	E
Protective industrial	0.2	G
Quarries	2	F
Railroad Yards:		
Receiving	0.1	G
Classification	0.2	G
Shipyard construction	5	E
Storage yards	1	G

[1] Compiled by Walter Sturrock in collaboration with the technical staff of the Nela Park Engineering Department, General Electric Company and reprinted from *Magazine of Light*, No. 6, 1941.

* See Fig. 126 and notes accompanying it.

CALCULATING COEFFICIENTS OF UTILIZATION

Coefficients of Utilization can be calculated from candlepower-distribution data by using the three-curve calculation method.[1] This method consists simply of separating the average candlepower-distribution curve of the luminaire into three component curves shown in Fig. 216.

The weighted average candlepower-distribution curve and the three component curves shown are for the luminaire whose distribution was given in Fig. 86 and for which the lumens were computed in Table 25. It will be seen that the horizontal component distribution curve is a circular "cosine" curve whose maximum value is equal to the candlepower of the test curve at 90 deg. The lumens represented by such a circular distribution curve are approximately equal to ten times the maximum candlepower value, or ten times the 90-deg. candlepower value. (In this case, the horizontal component lumens equal 582.) The lumens in the indirect component are then obtained by subtracting one-half the horizontal component lumens from the

[1] WARD HARRISON and EARL A. ANDERSON, "Coefficients of Utilization," *Transactions of the Illuminating Engineering Society*, March, 1920.

90 − 180 deg. lumens, in this case

$$2929 - 582/2 = 2929 - 291 = 2638 \text{ lumens.}$$

Similarly, the lumens in the direct component are found by subtracting half of the horizontal component lumens from the

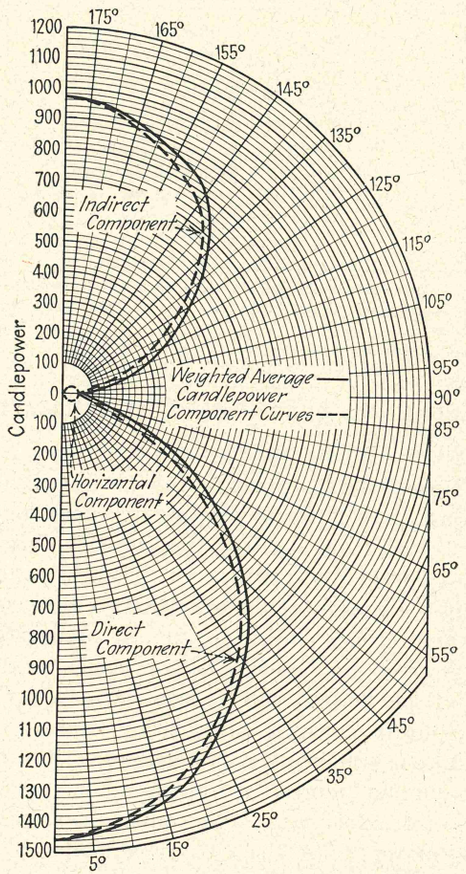

FIG. 216.—The three-component distribution curves of the direct-indirect fluorescent luminaire of Fig. 86 and Table 25.

actual 0 to 90 deg. lumens of the luminaire, or

$$3510 - 582/2 = 3510 - 291 = 3219 \text{ lumens.}$$

The algebraic sum of the lumens in the three component curves will equal the lumens in the original test curve, *i.e.*,

$$582 + 2638 + 3219 = 6439.$$

Coefficients of Utilization giving the proportion of useful lumens that result from each lumen in the various component curves have been determined experimentally and can be found in the I.E.S. paper above referred to. A complete listing of these coefficients is beyond the scope of this manual. However, to

TABLE 40.—INDIRECT COMPONENT COEFFICIENTS OF UTILIZATION

Room Index	75% ceiling 50% walls	50% ceiling 30% walls
B	.535	.33
E	.415	.24
H	.29	.16

TABLE 41.—HORIZONTAL COMPONENT COEFFICIENTS OF UTILIZATION

Room Index	75% ceiling 50% walls	50% ceiling 30% walls
B	.62	.46
E	.475	.34
H	.32	.22

TABLE 42.—DIRECT COMPONENT COEFFICIENTS OF UTILIZATION

Room Index	Broad		Medium		Narrow	
	75% ceiling 50% walls	50% ceiling 30% walls	75% ceiling 50% walls	50% ceiling 30% walls	75% ceiling 50% walls	50% ceiling 30% walls
B	.885	.83	.905	.85	.915	.86
E	.755	.69	.785	.73	.805	.76
H	.605	.54	.635	.58	.665	.62
	Very narrow		Concentrating		Focusing	
B	.925	.87	.93	.88	.935	.89
E	.825	.79	.845	.81	.855	.83
H	.695	.65	.715	.68	.735	.71

facilitate the computation of "square feet per lamp" values for the six room proportions and wall and ceiling reflectivities used in the simplified design, or "pocket-guide" method, given in

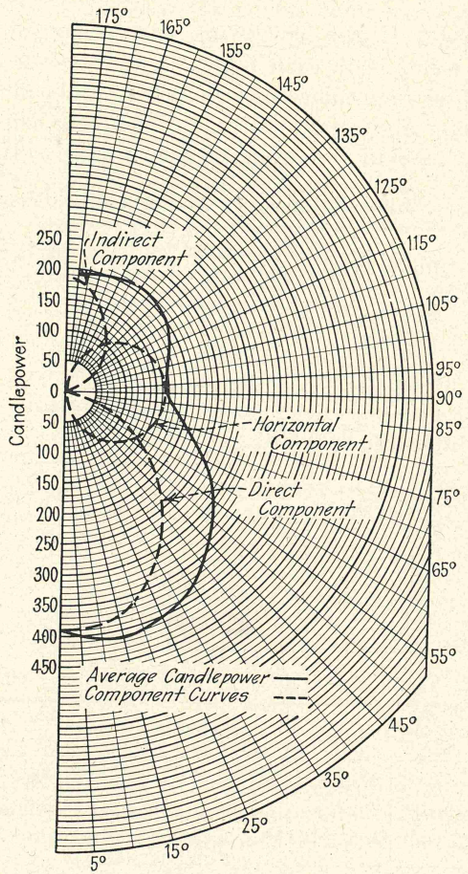

FIG. 217.—This illustration is included to show the three component distribution curves more clearly for a luminaire (Fig. 83 and Table 24) whose candlepower at 90 deg. is more appreciable than the unit shown in Fig. 216.

Chap. VII, the necessary Coefficients of Utilization for the three components are given in Tables 40, 41, and 42.

It will be noted that the Coefficient of Utilization for the direct component depends on the type of downward distribution. Obviously, the coefficient will be higher if the lumens are directed more sharply downward and have less opportunity to suffer absorption at the side walls. Therefore, the degree to which the downward component is classified as "broad" or "focusing" is based on the percentage of downward lumens in the 0- to 40-deg. zone as follows:

$$\text{Percentage of light in 0 to 40° zone} = \frac{\text{total lumens in 0 to 40° zone} - 0.65\ (\text{candlepower at 90°})}{\text{total lumens in 0 to 90° zone} - 5.0\ \ (\text{candlepower at 90°})}$$

The following shows how the direct components are classified:

Classification	Percentage of Light in the 0 to 40° Zone
Broad distribution	35–40
Medium distribution	40–45
Narrow distribution	45–50
Very narrow distribution	50–55
Concentrating distribution	55–60
Focusing distribution	60 and up

The actual coefficient for a given Room Index and ceiling and wall reflection factors can be determined by multiplying the lumens in the indirect, horizontal, and direct components of a particular luminaire by their appropriate Coefficients of Utilization (such as are given in Tables 40, 41, and 42), summing up the useful lumens, and dividing by the total lamp lumens. To illustrate this procedure, the data on Table 25 (shown graphically in Fig. 216) will be used to determine the Coefficients of Utilization necessary for the simplified design procedure of the type shown in Fig. 132.

Candlepower at 90° = 58.2
Horizontal component lumens = 58.2 × 10 = 582
Lumens in the 90 to 180° zone of the luminaire (as obtained from Table 25) = 2929
Lumens in the 0 to 90° zone = 3510
Lumens in the 0 to 40° zone = 1757

$$\text{Indirect component lumens} = 2929 - \frac{582}{2} = 2638$$

$$\text{Direct component lumens} = 3510 - \frac{582}{2} = 3219$$

Horizontal component lumens = 582

Total = 2638 + 3219 + 582 = 6439 (which checks the arithmetic, since the sum of the lumens in the three component curves must equal the total lumens emitted by the luminaire)
Percentage of light in the

$$0 \text{ to } 40^\circ \text{ zone} = \frac{1757 - (0.65 \times 59.2)}{3510 - (5 \times 59.2)} = 53 \text{ per cent,}$$

so the classification of the direct component is "Very narrow."

Coefficient of Utilization for *B* room with a 75% ceiling and 50% walls:

Useful lumens from indirect component
$= 2638 \times 0.535 = 1411$
Useful lumens from horizontal component
$= 582 \times 0.62 = 361$
Useful lumens from direct component
$= 3219 \times 0.925 = 2979$
Total useful lumens = 1411 + 361 + 2979 = 4751

$$\text{Coefficient of Utilization} = {}^{4751}\!/_{8400} = 0.57$$

In like manner the coefficients for the other five conditions can be obtained, the results being:

B Room Index with 50% ceiling and 30% walls
— Coefficient of Utilization = 0.47
E Room Index with 75% ceiling and 50% walls
— Coefficient of Utilization = 0.48
E Room Index with 50% ceiling and 30% walls
— Coefficient of Utilization = 0.40
H Room Index with 75% ceiling and 50% walls
— Coefficient of Utilization = 0.38
H Room Index with 50% ceiling and 30% walls
— Coefficient of Utilization = 0.32

It is well to point out that in some cases the subtraction of one-half the horizontal component lumens will leave a negative direct or indirect component. The calculations are carried through in the same manner, however, except that the useful lumens of the component curves are added algebraically, which means that the negative component lumens will be subtracted in obtaining the total useful lumens.

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